2019

Sustainable shoe design and evaluation using kinematic and kinetic analysis

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by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Apparel, Merchandising, and Design

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my co-major professors, Drs. Young-A Lee and Chunhui Xiang for their thoughtful guidance, mentorship, support, and encouragement for creativity throughout my academic journey to doctoral degree. I am also very thankful to my committee members for their various help, Dr. Eulanda Sanders, Dr. Guowen Song, Dr. Jason Gillette, and Dr. Daniel Russell.

Dr. Sanders, the department chair of Apparel, Events, and Hospitality Management, has given me consistent support, and has not only inspired me, but also encouraged me to finish this dissertation. Drs. Song and Gillette have allowed me to use a textile testing laboratory and a biomechanics laboratory, respectively. Dr. Gillette not only trained me to take a kinesiology approach to my research in his seminar, he also helped me challenge myself to apply both kinematic and kinetic approaches and methods to my research. I also want to thank Dr. Russell. In his class (Advance Quantitative Method), I learned to think critically for research methods and write my academic papers.

Part of this dissertation was funded by the United States Environmental Protection Agency P3 Phase II "Developing Sustainable Products Using Renewable Cellulose Fiber and Biopolymer Composites" (US EPA Grant No. SU835733). Furthermore, Study 2 for the material testing part "Multi-layered cellulosic material as a leather alternative in the footwear industry, 37(1), 1-15" was published (2019) in the *Clothing and Textiles Research Journal*.

In addition, I want to extend my appreciation to my friend and colleague Mitch Stephenson for his help and support for my wear testing in a biomechanics lab. He spent many days to help me complete the wear testing. I also want to extend special thanks to Dr. Susan Fiorito (Director of the Jim Moran School of Entrepreneurship at Florida State University) and

Drs. Woong Kwon, Seong-Kwan Cho, Byung-Hoon Woo, Young Do Kim, Sophia Min, and Junsig Wang for their encouragement and help during my academic years. I would also like to thank all my friends who spent time hanging out with me in Korea and United States for keeping me strong.

Very importantly, I want to thank my parents in Korea and my sister family in the United States, who always helped and supported me when I needed it. They deserve much credit for my completion of my doctoral degree. I feel confident and ready to start my new journey.

THANK & LOVE YOU ALL!

ABSTRACT

The purpose of this study was to investigate the compatibility of sustainable shoes made with bacterial cellulosic (BC) non-woven mat integrating with eco-friendly materials, compared with durability and comfort in performance of newly developed sustainable shoes and commercially available leather shoes via users' wear testing. This study also examined wearers' perceptions and acceptance in the sustainable shoes, compared with leather shoes via survey questionnaire. The specific research objectives of this study were to: (a) identify a proposed integrated theoretical framework for sustainable shoe design, (b) examine a multi-layered cellulosic material (MCM) by bonding BC non-woven mats, denim fabric, and hemp fabric compared with those of two-layered leathers, multi-layered calf-skin leather and pig-skin leather (MCPL), (c) develop sustainable shoe prototype made of MCM through IsAcT design process, (d) evaluate wearers' performance in men's commercial leather shoes comparing with sustainable shoes, and (e) assess wearers' perceptions and acceptance of the sustainable shoes comparing with the leather shoes.

Based on the proposed integrated theoretical framework, for material test hypotheses, these two materials would have similar properties. No significant mean differences were found between MCM and MCPL in total heat loss and break force. The values of air permeability, evaporative potential, and permeability index of MCM were higher than those of MCPL. The findings of this study confirmed the effectiveness of MCM for use as a leather alternative material when developing sustainable shoes and provide insights to the footwear industry. After that, therefore, five pair of sustainable shoes were made with MCM and the other eco-friendly materials (compressed papers and cork materials).

For wear testing, it was hypothesized that there were no differences in kinetic and kinematic parameters of gait within lower extremity of participants wearing the leather shoes and sustainable shoes while performing the following three conditions: walking on flat ground, ascending, and descending stairs. A total of 37 human subjects were used for the data analysis. For kinetics, no statistically significant mean differences between the two shoes during descending stairs was identified. For kinematics, no statistically significant differences for peak angles of hips, knees, and ankles were found between the two shoes during ascending and descending stairs. The findings of this study confirmed the possibility of men's sustainable shoes made with MCM as a leather alternate in terms of kinematics and kinetics.

Finally, a total of 42 male subjects were participated in this experimental study and their responses were used for data analysis. A paired t-test was performed to examine whether there were significant mean differences between the sustainable shoes and leather shoes, in the following five dimensions: function, expression, aesthetics, mobility related with physical fit and comfort during wear trials, and wearers' acceptance. The findings demonstrated that the men's shoes made with the eco-layered material configuration (MCM), which can be a leather substitute, have the potential to attract young male consumers in the future. However, the sustainable shoes in this study still remained a lack of mobility related to fit and comfort. Suggestions for future research to enhance the mobility of sustainable shoes for providing better fit and comfort of wearers are discussed.

CHAPTER 1. INTRODUCTION

Recently, sustainable practices have not only lead to the development and benefits of companies, but also have contributed to current and future consumers' well-being and welfare. Sustainable practices are associated with protecting exhaustion of resources, saving water and energy, maintaining a healthy workplace, as well as reducing and/or recycling materials to minimize the impact on our environment presented by the American Apparel and Footwear Association (AAFA, 2015a). Sustainability practices have been applied in wide-ranging fields such as sustainable communities, green technology, sustainable transportation, and green chemicals according to the United States Environmental Protection Agency (U.S. EPA).

For the past few decades, the fashion industry has consistently approached and implemented sustainability practices in their product development processes. The use of varied and large amounts of materials have prompted the transition to using sustainable practices, as the industry is confronted with environmental problems, including carbon footprint in landfills, which cause a scarcity of land and high costs. To be specific, the footwear industry engages in producing a variety of shoes (e.g., dress/casual shoes, sneakers, boots, athletic shoes, and flip-flops) and parts (e.g., lace, buckle, and insole) of footwear (The New York Time, 2017). As presented in Table 1.1, various waste items and materials (e.g., urethane, synthetic textile, rubbers, and leather) used for footwear development take a long time to completely decompose in landfills (LeBlanc, 2017). For example, leather not only takes approximately 50 years to fully decompose without being recycled or reused, but also has emerged as the biggest concern, because of the required tanning process, which uses harmful chemicals (e.g., methane and chlorine; Grahame, 2014; LeBlanc, 2017).

Table 1.1. *A Time Taken by Waste Items to Decompose*

Items	Life time	Main type of material
plastic bags	10-1000 years	plastic
plastic bottles	450 years or more	plastic
foamed plastic cups	50 years	Plastic
aluminum cans	200-250 years	metal
tin cans	50 years	metal
tinfoil	It does not biodegrade	metal
glass waste	1000000 years	glass
paper waste	2-6 weeks	paper
train tickets	2 weeks	paper
milk cartons	5 years	paper
cardboard	2 months	paper
plywood	1-3 years	wood
painted board	13 years	wood
rubber-boot sole	50-80 years	rubber
leather shoes	25-40 years	fiber
leather	50 years or more	fiber
nylon Fabric	30-40 years	fiber
wool clothing	1-5 years	fiber
cotton Glove	3 months	fiber
canvas products	1 year	fiber
disposable diapers	250-500 years	fiber
ropes	3-14 months	fiber
monofilament fishing line	600 years	fiber
food waste	1-6 months	-
lumber	10-15 years	-
cigarette butts	10-12 years	-
batteries	100 years	-
sanitary pads	500-800 years	-
styrofoam	It does not biodegrade	expanded polystyrene

Note. Modified and adapted from the decomposition of waste in landfills: A story of time and materials by Leblanc (2018).

The footwear industry continues to make efforts to minimize energy, to reduce the use of chemical materials, and to enhance material efficiency during manufacturing process for footwear, due to societal and consumer movements for the emphasis on sustainability. Along with the industry's movement towards sustainable practices and as consumers' environmental consciousness increases, there are gradually shifting attitudes toward purchasing eco-friendly footwear and/or apparel and recycled products in a positive manner. However, the industry has contributed to serious environmental, social, and economic issues, because of the rapid change in the footwear market in fashion trends as well as the short lifespan of footwear (Staikos & Rahimifard, 2007). It is still challenging for footwear designers and manufacturers to produce sustainable shoes, due to limited: (a) theoretical frameworks, (b) information about eco-friendly materials, and (c) their appropriate application into product development, which will eventually reduce negative environmental impacts on ecosystems and keep human health in balance.

One of well-known existing frameworks is an environmental design certification standard called cradle-to-cradle (C2C), developed by McDonough and Braungart (2002). The C2C framework fundamentally seeks not only to reduce or minimize the damage to and the negative effects on the environment, but also to embrace eco-effectiveness in order to protect our nature, human health, and a balanced ecosystem (McDonough & Braungart, 2002). A few global fashion companies (e.g., Nike, Gucci, and Patagonia) in apparel and footwear have made footwear, apparel, and accessories using biodegradable or recyclable materials following by the C2C design guideline (Pasolini, 2013). Despite the continuous efforts for implementing sustainable practices in the footwear industry, as of now, limited theoretical frameworks exist for sustainable footwear design and product development, which can be used as concrete models for researchers, designers, and educators.

The use of new materials and structures of shoes are prominent factors in creating footwear (e.g., Heelless, Masai, Flyknit, and ZigTech shoes), because these variables are not only considerably linked to the aesthetic exterior of shoes with fashionable attributes, including colors and styles, but also significantly enhanced function and comfort of the footwear (Braithwaite, 2014). Footwear is a necessary piece of garment worn on the feet to protect against diverse environments as well as temperatures, and provides comfort (Murley & Landorf, 2012);

however, limited research exists investigating material testing and structures for sustainable footwear. With regard to shoe design, footwear's comfort and fit are essential factors and critical issues to satisfying customers' needs and desires (Au & Goonetilleke, 2007). First, footwear's comfort is influenced by shoes' material properties, structures, fitting, weight, insoles, and the inside temperature of the shoes (Au & Goonetilleke, 2007). Second, footwear's fit presents a direct correlation between the shape of wearer's feet and the inside shape of the shoes (Hawes et al., 1994). Consequently, the discomfort and unfit shoes not only impair individuals' mobility and standing, but also may cause pain, fatigue, and stress during walking. Furthermore, footwear might inadvertently lead to foot injuries and disorders, slips, trips, as well as falls. To evaluate comfort and function of shoes, the design and production of a new pair of shoes needs to implement users' wear testing using kinetic and kinematic gait analysis, which have broadly been used from pathology clinic to biomechanics, and identified characteristic features and walking patterns of potential wearers. However, limited academic research is available in terms of comfort and function of newly developed sustainable shoes (Cao et al., 2014b) using a biomechanical approach in the footwear, product development, and biomechanics fields.

Ultimately, the findings of this study could contribute suggestions for manufacturers, shoes designers, eco-activists/experts, and researchers in providing possible ways to implement sustainable practices in product development processes with an integrated theoretical framework for sustainable shoe design, validate commercial viability of sustainable materials, and investigate wear testing for the footwear made with eco-materials. Overall this research proceeded four studies: (a) integrated theoretical framework, (b) material testing, (c) sustainable shoe prototype, and (d) wear testing including kinematic and kinetic approaches as well as wearers' perceptions and acceptance (see Figure 1.1).

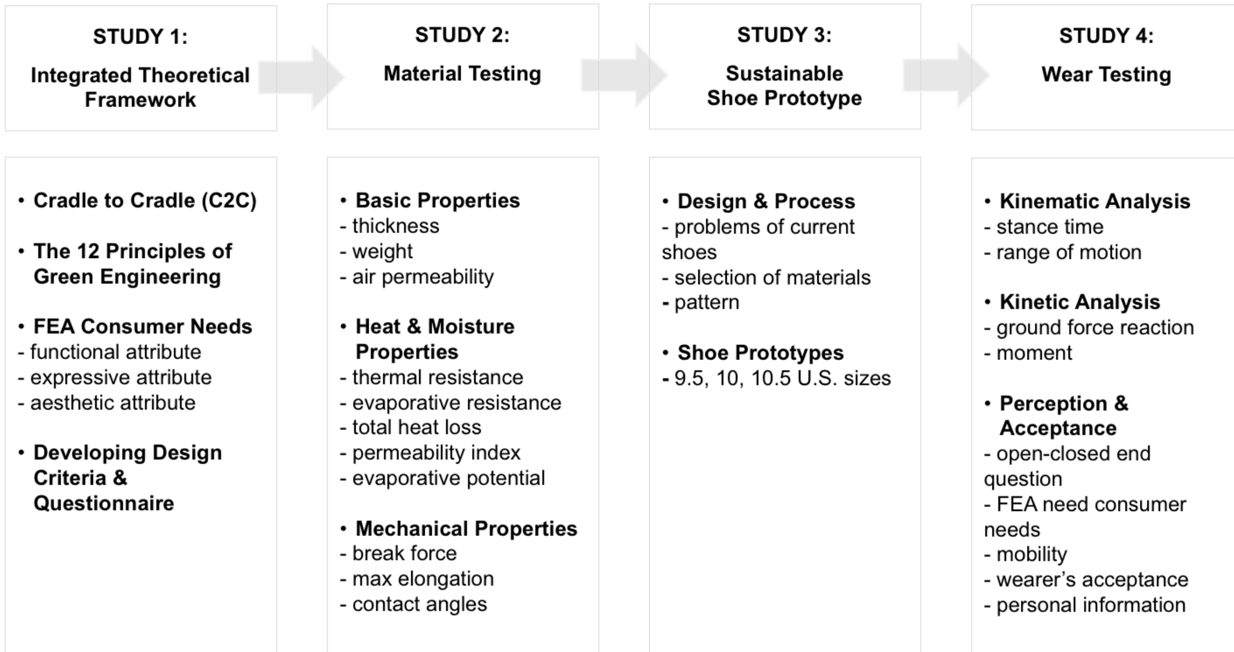


Figure 1.1. Four studies of this overall research.

Purpose and Specific Objectives

This work was part of the larger project, EPA P3 Phase II "Developing Sustainable Products Using Renewable Cellulose Fiber and Biopolymer Composites" (U.S. EPA Grant No. SU835733) focusing on the development and evaluation of bacterial cellulosic (BC) non-woven mat (or BC fiber mat) for the use in sustainable apparel or apparel-related production. Within this large scope, this study aimed to investigate the compatibility of sustainable shoes made with BC material integrating with eco-friendly materials, compared with durability and comfort in performance of newly developed sustainable shoes and commercially available leather shoes via users' wear testing. This study also examined wearers' perceptions and acceptance in the sustainable shoes, compared with commercial leather shoes via a web-based questionnaire. The five specific research objectives of this study were to:

1. Identify important design criteria and develop a conceptual framework for sustainable shoes under the cradle-to-cradle (C2C) design framework by incorporating the 12 principles of green engineering and wearers' functional-expressive-aesthetic needs (Study 1).
2. Examine the properties of selected single-layered materials (bacterial cellulosic non-woven mat, denim fabric, hemp fabric, calf-skin leather, and pig-skin leather) and two multi-layered materials (MCM and MCPL), which evaluated the compatibility of MCM as a leather alternate (Study 2).
3. Design and develop men's sustainable shoes made with bacterial cellulosic non-woven mats, denim fabrics, hemp fabrics, compressed papers, and cork materials (Study 3).
4. Evaluate wearers' performance of shoes by using quantitative kinematic and kinetic parameters of lower body movements, which lead to prove the compatibility of BC-based sustainable shoes as leather-based commercial shoes (Study 4).
5. Assess wearers' perceptions and acceptance of the men's sustainable shoes compared with commercial leather shoes via a survey questionnaire (Study 4).

Theoretical Framework

This study used an integrated theoretical framework, the cradle-to-cradle design process for sustainable shoes, adapted from the following theoretical elements: The Cradle-to-Cradle (C2C) Design Model (McDonough & Braungart, 2002) and the Functional-Expressive-Aesthetic (FEA) Consumer Needs Model (Lamb & Kallal, 1992). This study also adapted Anastas and Zimmerman's (2003) 12 principles of green engineering and incorporated these within the shoe development process to turn a sustainability practice vision into reality for footwear industry. The integrated framework focused on selection of eco-friendly materials, design process, and evaluation of sustainable shoe prototypes to be used as a theoretical guide to conduct each stage of this research (see Figure 1.2). More details of this framework are shared in the Chapter 2.

Significance of the Study

This study has significant impacts on the development of the sustainable and/or wearable product design process, the evaluation of multi-layered cellulosic material (MCM) properties, and the understanding of gait analysis of lower limbs with respect to men's sustainable shoes through biomechanical approach as well as an assessment of appearance and comfort in multiple movements.

First, the integrated theoretical framework for the sustainable shoe design process will be a useful tool for teaching for students, instructors, and designers to enhance their creative problem-solving skills in sustainable practices in academic areas. As shown in Figure 1.2, the design and processing stages, thus, may assist designers and textile scientists in developing new products in textile science, sustainable practice, and footwear industry areas.

Second, properties of MCM could possibly translate into a guideline of sustainable footwear and other eco-friendly products.

Third, it is useful for testing material properties and hypotheses, and discerning if consumers' acceptance could assist in identifying area for exploratory research.

Finally, rarely do shoe designers and researchers investigate differences between men's sustainable (biodegradable) shoes and leather shoes during walking using kinematic and kinetic approaches. Furthermore, a few additional studies have been performed to investigate the effects on sustainable shoes for users' acceptance and perceptions in this research area. Therefore, all results of this study may provide effective insights and practical implications in creating sustainable shoe design and other eco-friendly and/or wearable products in dynamic areas. Moreover, this study can offer that male segment makes theoretical contributions and generates valuable suggestions for male shoe designers and marketing managers in footwear industry.

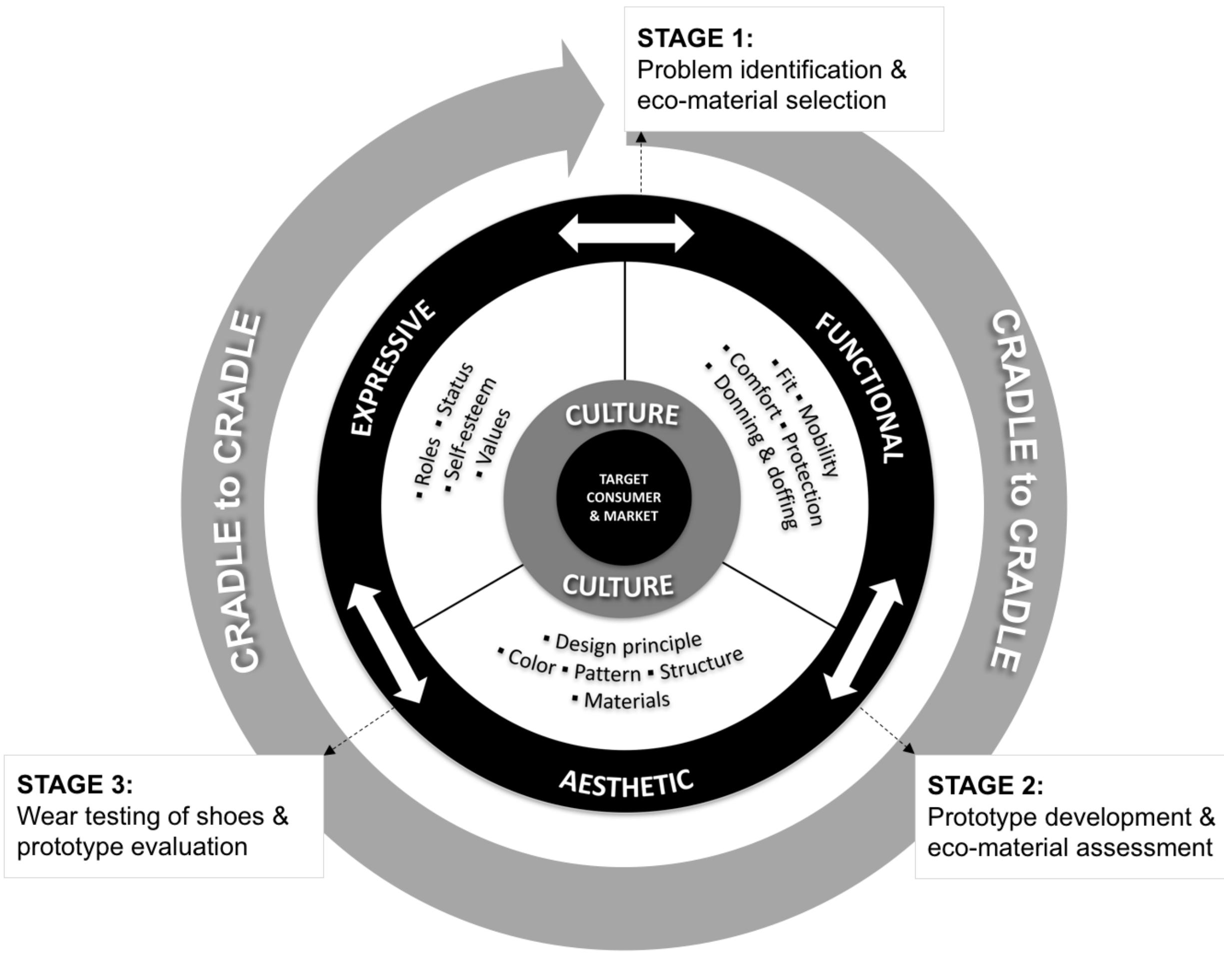


Figure 1.2. Proposed theoretical framework for sustainable footwear design.
Note. This framework modified form Lamb and Kallal, 1992, p. 42.

Definitions of Terms

Abduction and adduction: "Take place in the frontal plane, where the distal segment moves away or towards the midline of the body relative to the proximal segment, respectively" (Levine, Richards, & Whittle, 2012, p. 2).

Aesthetic needs: The desire for beauty of clothing or equipment by use of factors such as line, form, color, texture, and pattern to create a pleasing design (Lamb & Kallal, 1992). and lower portions (Levine et al., 2012).

Apparel industry: A wide variety of clothing and textile manufactured including fashion industry (Vault, 2017).

Bacteria cellulosic (BC): “A nearly-purified cellulose that is produced by acetobacter species cultivated in culture medium containing carbon and nitrogen sources” (Nakagaito, Iwamoto, & Yano, 2005, p. 93).

Calf-skin: “For trade convenience such are called “calf-skin” those weighing from fifteen to twenty-five pounds, “kips” and all above twenty-five pounds are called hides. it makes a strong pliable leather highly susceptible to polish and to suede finish. It has long been in use for all kinds of shoes” (Allen, 1922, p. 384).

Comfort: A pleasant state generating from physiological, psychological, and physical balances between a human being and the environment (Slater, 1985).

Coronal plane (frontal plane): One plane which divides the whole body into front and back portions (Levine et al., 2012).

Cradle-to-cradle (C2C): “The design and production of products of all types in such a way that at the end of their life, they can be truly recycled (upcycled), imitating nature’s cycle with everything either recycled or returned to the earth, directly or indirectly through food, as a completely safe, nontoxic, and biodegradable nutrient” (Sherratt, 2013, p. 630).

Dress (casual) shoes: Wearing shoes made of leather, upper part (vamp) of the shoes, with a suit (casual pants, or jeans), commonly referring to business shoes, dress shoes, or causal shoes (Abimbola, 2017). In this study, the terms dress shoes and casual shoes are used interchangeably with dress shoes.

Expressive needs: Elements that convey particular messages about the wearer in terms of identity, roles, status, and self-esteem to enhance the communicative and symbolic aspects of clothing/equipment (Lamb & Kallal, 1992).

Fashion industry: "Comprising designer and basic clothing, footwear and accessories is highly complex and characterized by short runs, fast turnover and a diverse range of products channeled through a fragmented and frequently changing supply chain distributed over many global location" (Black, 2012, p. 9).

Flexion and extension: "Take place in the sagittal plane; in the ankle theses movements are called dorsiflexion and plantarflexion, where the foot (distal segment) moves up or down relative to the tibia (proximal segment), respectively" (Levine et al., 2012, p. 2).

Footwear: The covering of the feet, generally referring to shoes, but also incorporating socks, leggings, and other coverings (DeMello, 2009).

Force platform: Equipment to measure direction and magnitude of the ground reaction forces generated by pressure beneath the foot of a human or animal (Whittle, 2014).

Functional needs: The utility of items that to provide the wearer components of comfort, fit, protection, safety, balance, mobility, and donning/doffing (Lamb & Kallal, 1992).

Gait analysis: "Systematic measurement, description and assessment of those quantities thought to characterize human locomotion" (Davis et al., 1991, p. 575).

Gait cycle: "The period of time from the point of initial contact (also referred to as heel strike) of the human foot with the ground to the next point of initial contact of that same limb. A cycle of gait is divided in stance phase and swing phase" (Ounpuu, 1994, p. 3).

Insole: The foundation of the shoes; the initial stage is to nail the insole to the last (Vass & Molnár, 2006, p. 207).

Internal and external rotation: "Take place in the transvers plane; called medial and lateral rotation, respectively, the term referring to the motion of the anterior surface of the distal segment relative to the proximal" (Levine et al., 2012, p. 3).

Inverse dynamics: "To measure the net effect of all of the internal forces and moments of force acting across several joints" (Robertson et al., 2004, p. 104).

Joint angle: The angle between the longitudinal axes of two adjacent body segments usually measured in degree (Robertson et al., 2004).

Joint moments: "An observed joint movement that shows the effect of the total moment that acts at the joint at the instant during the gait cycle and indicates contraction either flexor or extensor muscle (Winter, 1984, p. 64).

Joint motions: "Adjacent joint may have different directions for the same type of motion" (Robertson et al., 2004, p. 27).

Kinematics: "The study of motion without regard to the force that cause that motion" (Robertson et al., 2004, p. 17).

Kinetics: "The study of force, moments, mass and accelerations" (Levine et al., 2012, p. 26).

Last: the mechanical foot-shape form that offer shoemakers with the fundamental for building a shoe (Tyrrel & Carter, 2009).

Leather: "The tanned skin of animals and usually refers to the skin of cows" and other animals (DeMello, 2009, p. 195).

Life-Cycle Assessment: A guideline to evaluate the potential natural environmental impacts, human health, and resources used throughout a product's life-cycle (ISO, 2006).

Locomotion: "The hallmark that distinguishes organisms in the Animal Kingdom from plants, and animals have devised myriad methods to enable movement" (Robertson et al., 2004, p. 1).

Mobility: "The ease with which an articulation, or a series of articulation, is allowed to move before being restricted by surrounding structures" (Kreighbaum & Barthels, 1996, p. 64).

Moisture absorbency: “The ability one material (the absorbent) to take in or absorb another material (the absorbent)” (Kadolph, 2010, p. 542).

Motion capture system: The process of recording and calculating performance and the movement of human or animal with reflective markers using multiple cameras and high technical hardware and software (McGinnis, 2013).

Product development process: A series of interconnected procedures at every product development stage, which are connected to resources to generate output (Papinniemi, 1999).

Product development: “Design and engineering required for products to be serviceable, producible, salable, and profitable” (Glock & Kunz, 2005, p. 641).

Range of motion (ROM): The range of motion (ROM) at each joint (e.g., hip, knee, and ankle) in the low limbs refers to the total amount of angular displacement and direction through movement between two adjacent segments using a motion capture (Kreighbaum & Barthels, 1996).

Sagittal plane (median plane): One plane which divides the whole body into right and left portions (Levine et al., 2012).

Sustainability: “Conformance with principles of sustainable development, encompassing the environmental, health and safety, social, economic, and ethical aspects of a corporation or other entity” (Fiksel, 2009, p. 383).

Sustainability practices: To be considered as a strategic practice or measurement that means the simultaneous pursuits of environmental, economic, social, and operational performances in a variety of fields (Cheon & Deakin, 2010; The United States EPA).

Sustainable (eco-friendly) shoes: Footwear as a product that covers all portion of foot using eco-friendly materials and/or upcycling considering a simple pattern development through zero waste approach in this study.

Tensile strength: “The strength of a material’s resistance to the continuation of a tear” (Kadolph, 2007, p. 553).

Transverse plane (horizontal plane): one plane which divides the whole body into upper and lower portions (Levine et al., 2012).

Wearability: the term used for apparel related to function of product (Kadolph, 2007).

Assumptions

In this section, the assumptions of the study are stated in two categories: (a) theoretical assumptions and (b) method and procedural assumptions.

Theoretical Assumptions

An integrated theoretical framework in this study was adapted from the following theoretical elements: (a) the Cradle-to-Cradle (C2C) design model (McDonough & Braungart, 2002), (b) the Functional-Expressive-Aesthetic (FEA) consumer need model (Lamb & Kallal, 1992), (c) sustainable apparel and product design processes (Cao et al., 2014b), and (d) 12 principles of green engineering developed by Anastas and Zimmerman (2003). Therefore, this study will not only provide effective understanding in creating sustainable shoe design and other eco-friendly and/or wearable products in dynamic areas, but will also offer that male segment makes theoretical contributions and generates valuable suggestions for sustainable shoe designers and marketing managers in footwear industries.

The following theoretical assumptions were made for this study:

1. Footwear is the most proximal human-built environment of human beings and meets various levels of needs.
2. Human beings fulfill their various levels of psychological and physical needs through footwear.
3. Sustainable footwear implements users' various level of psychological and physical needs and wants.

Method and Procedural Assumptions

This study can identify the effectiveness of a multi-layered cellulosic material (MCM) for use as a leather alternative material when developing sustainable shoes and provide insights to the footwear industries. Moreover, this study can not only investigate the possibility of men's sustainable shoes made with MCM as a leather alternate in terms of kinematics and kinetics, but also, the men's shoes made with the MCM, which can be a leather substitute, have the potential to attract young male consumers in the future. The following method and procedural assumptions were made for this study.

1. Properties of the MCM (including BC non-woven mat, denim fabric, and hemp fabric) could provide the feasibility of developing other sustainable products.
2. Participants are able to address their needs and evaluate the design qualities of both sustainable shoes and commercial dress shoes.
3. The sustainable shoes design and process for this study can apply to the majority of small footwear companies in the globe.

CHAPTER 2. LITERATURE REVIEW

To propose a concrete theoretical framework to guide this study, especially for the sustainable shoe design and development, as well as its evaluation, this chapter first reviews previous theoretical models and studies regarding sustainability and product development. This chapter also addresses the issues and trends regarding the current footwear industry and sustainable materials and their properties to design and develop better sustainable shoes. Finally, this chapter presents gait analysis with both kinetic and kinematic approach, and an evaluation of the sustainable shoes in order to comprehend consumers' acceptance, perceptions, and comfort. In summary, the sequence covers: (a) trends in the footwear industry, (b) problems of men's dress shoes, (c) key elements of shoes design and development, (d) sustainable design process models, (e) product development process models, (f) an integrated theoretical framework that is grounded for this study, (g) sustainable materials and properties, (h) thermal comfort of material properties, (i) structures and movements of lower extremity, (j) gait analysis, and (k) consumer's perceptions. Based on the literature reviews, the chapter proposes hypotheses to examine the relationships among variables.

Trends in the Footwear Industry

Footwear, which people wear every day, is important and necessary object, because it protects consumers' feet from different weather conditions, workplace situations, dangerous objects, and uneven surfaces (Huff, 2010). Historically, shoes hand-made by craftsmen were popular until the end of the 19^{th} century, because consumers sought protection for the delicate structures of their feet and the uniqueness regarding shapes, models, leathers, and colors of individual shoes (Vass & Molnar, 2006). However, the development of an automatic machine created by Jan Ernst Matzeliger (1852-1889) and a shoe sewing machine invented by Lyman

Reed Blake (1835-1883) for efficiency in making shoes prompted the mass production of affordable shoes in the footwear industry (Bellis, 2015).

The American Apparel and Footwear Association (AAFA, 2015b) reported that, in comparison with other industries (e.g., alcohol, automobile, and toy), the apparel and footwear industries in the United States reached approximately $361 billion in 2013. The global footwear market annually generates over $52.1 billion (Statistic Brain Research Institute, 2016). According to the AAFA (2015b), the consumption of shoes gradually increased 8.5% between 2011 and 2013. On average, the United States consumers who individually own 14 pairs of shoes spend over $29.7 billion on footwear-related purchases per year (Ilyasgov, 2015; Statistic Brain Research Institute, 2016). Surprisingly, in 2013, within the footwear industry, men's footwear generated the largest sales (9%) followed by children's footwear (3%) and women's footwear (2%), as compared to growth documented in 2012 (National Purchase Diary, 2014). Chapman (2013) reported that males have spent more time and money on shoe purchases than female shoppers, because they are becoming more conscious of the types of shoes that not only influence decisions about fashion styles, but also convey their personal character, identity, and occupation. Through developing social media, male consumers have also instigated fashion context, cost, and product differentiation in the footwear industry (Wright, 2014). While both population and pollution have continually grown, natural resources (e.g., coal, oil, and gas) have decreased in the world (Behr & Johnen, 2014).

Nowadays, the shoes are a fashion item. Since swift changes in fashion market and fashion trends (Srinivas, 2015), the useful lifespan of shoes is relatively short and steadily decreasing. To reduce costs, manufacturers often use cheap and harmful materials (e.g., artificial leather, plastic, xylene, and synthetic/inorganic fabric), while many shoes are easily thrown away in the landfills (Woodford, 2016). More than 20 billion shoes are manufactured a year in the United States, and over 300 million pairs of shoes are discarded into landfills (Colt, 2016). Production, consumption and post-consumption practices tend to pollute the water and land as well as bring a huge source of severe carbon emissions. However, many footwear shoppers have not paid much attention to the negative impact of footwear and its industry on the environment. This industry has been contributed to the negative environmental impact, as well as the workers' health problems (e.g., aplastic anemia, cancer, and leukemia), for the past few decades (Tarantola, 2014). In response to this urgent cause and because of increasing sustainability awareness from various stakeholders, the footwear industry has been actively developing and incorporating eco-friendly materials into their new product design and development.

Shoes are commonly made of diverse materials (e.g., synthetic fiber, rubber, polyurethane, and leather) that are hard to be fully decomposed (Grahame, 2014; LeBlanc, 2018). Sustainability practices in the footwear industry enable the protection of resources, conservation of water and energy, maintenance of a healthy workplace, and reduction and recycling of materials to minimize the negative impact on the environment (Heale, 2013). In terms of sustainable practices, many well-known footwear companies (Nike, Puma, and Adidas) have been developed sustainable footwear using recycled and innovative materials, including advanced technologies. For examples, such shoes from Puma are made of environmentally-responsible materials (synthetic ultra-suede upper leather; Puma, 2011). Nike and Adidas developed manufacturing process and sustainable shoes using Flyknit (i.e., Nike shoes) and Primeknit technologies (i.e., Adidas shoes) to reduce waste in product creation and to use recycled materials (Brettman, 2012). In addition, New Balance Athletics, Inc. produces sustainable shoes made from recycled material (i.e., plastic bottles) and a high quality polyester fabric, called "Eco-fi" (Curto, 2011). It means, in essence, that material selection is an important factor in creating new sustainable footwear. Wearers' comfort is another crucial attribute to consider when in the purchase of shoes; however, implementing sustainability attributes in footwear development and its production may not be enough to entice consumers to purchase eco-friendly footwear. Thus, understanding foot morphology (e.g., length, width, arch type, form, and structure) is essential in designing footwear.

Problems of Men's Dress Shoes

Men's dress shoes, which feature strong, durable, and decorative elements, tend to give men a luxurious, stylish, and tidy appearance (Attire Club, 2014). A pair of dress shoes made of leather are not only worn with a suit and tie for formal occasions (e.g., wedding, celebration, or job interviews), but also with casual pants or jeans for informal occasions (Abimbola, 2017). As shown in Figure 2.1, dress shoes are characterized by five different styles: (a) Berby shoes (open lacing style), (b) Oxford shoes (close lacing style with round toes and a cap), (c) Brogue shoes (perforations with visible edges of the material), (d) Monk shoes (no lacing styles, straps and buckles), and (e) Loft shoes (no lacing style, penny, bit, and tassel loafers; Sigala, 2014).

Figure 2.1. Different types of men's dress shoes.
Note. These shoes images were adapted by Quora.com linked to https://www.quora.com/What-are-the-different-types-of-mens-shoes

Wearing dress shoes for a long time often causes foot discomfort, pain, and fatigue, because dress shoes with a low heel have several common problems such as unfit, wrong shape, tightness/looseness around lacing, and/or heel slip (Leow, 2016). Leather shoes also often cause odor inside shoes, because leather has a lack of breathability. In addition, leather shoes have perpetual problems such as shoelaces and prices, because depending on shoes' brand, style, and leather quality, the cost falls into significantly different price ranges. For example, in order to reduce the shoes' cost, low quality leathers (related to tanning processes of leather and leather dye) were used to make the entire shells including outer shell inner shell of the shoe and outsole was made of polyurethane. Consequently, the production of materials and the design process for leather shoes can have large impacts on environmental issues and worker's health (Habib, Noor, & Musa, 2015; Suresh, Kanthimathi, Thanikaivelan, Rao, & Nair, 2001).

Key Elements of Footwear Design and Development

Footwear design and development can either strengthen healthy foot or deteriorate it. Not only do footwear designers consider of promotion of healthy and function of foot, but they also fulfill the consumer's demands for style of shoes and fashion. In particular, it is important for sustainable footwear to perform design processes and to select suitable materials, because 70% of manufacturing process of the sustainable product exerts a strong effect on the environment (Niinimäki, 2009). Moreover, the materials significantly influence the life of the footwear, and the end of life treatment of the product (Staikos, Heath, Haworth, & Rahimifard, 2006). For foot healthy and function, footwear is generally designed to be comfortable and stable in positions and gait is used for comfortably walking and protecting feet for a long time. Depending on different occupation and purposes (e.g., hiking, running, skiing, and fishing) for wearing footwear, the shoes are composed of different structures, shapes, colors, designs, and materials. Designing proper footwear tends to contribute to health and safe benefits such as reducing foot disorders and falling accidents (Tomczyk et al., 2014). Consequently, footwear designers should sufficiently understand human anatomy (foot morphology, structures of bones and joints), movement, and material's characteristics, because when standing, walking, and running, the bones and joints support weight of human body to sustain balance, to facilitate uneven surfaces, and to absorb shock, associated with comfort and fit (Moore, Dalley, & Agur, 2013).

Sustainable Design Process Models

A sustainable design approach could deal with an optimal solution to effectively create sustainable products or processes with less harmful environmental effects (Salari & Bhuiyan, 2018). A sustainable design framework can further contribute to a sustainable society, which strengthens the quality of human life (or well-being) as well as protects of the environment (ISO, 2006). The framework enables to develop design aspects of aesthetics, functionality, and product marketability for apparel designers (ISO, 2006). The design process needs to incorporate the sustainable design framework that guarantees positive environmental impact, which is closely related to the "Life-Cycle Assessment" of products (Fava et al., 1991; Klöpffer, 2012).

McDonough and Braungart's (2002) cradle-to-cradle (C2C) design process model is an effective tool for integrating sustainability into product design and development processes. The C2C concept focuses on designers' role in accomplishing sustainability practices and helps with sustainable product design, which enables the use of effective materials (reuse and/or renewal of materials), energy conservation, and economy in expenditures (McDonough, Braungart, Anastas, & Zimmerman, 2003). C2C has been a useful tool for integrating sustainable performance into design processes and/or business plans. The guideline pertaining to the C2C identifies three key tenets: (a) waste equals food, (b) use of current solar income, and (c) celebration of diversity. Therefore, eco-friendly products are feasibly designed in the best ways to minimize chemicals or natural resources use and utilize renewable or alternative energy sources.

Sustainable products also supply either biological nutrients (e.g., food in the cycle of nature) or technical nutrients (e.g., desirable industrial system) to bring effectiveness and conservation ways at the end of their lifecycles (McDonough & Braungart, 2002). The products using biodegradable or natural materials are continuously circulated into reuse, promoting less damage to our ecosystems in their entire life cycle, as opposed to cradle-to-grave as the lifecycle of products, the use at the end of a product's lifespan, without any recycling or reusing of the products and placement into landfills (McDonough & Braungart, 2002; McLennan, 2004).

McLennan (2004) presented five requirements to identify the C2C certified products. First, the materials can offer environmental safety and health to human life. Second, the recycling and composting processes of materials should be designed with consideration of the product. Third, the process of manufacturing the product brings about renewable energy and energy efficiency. Fourth, the product should make efficient use of water and generate a high quality of water. Finally, manufacturers or companies can develop effective strategies including environmental, social, and economic responsibility. Consequently, designers should not only understand issues regarding environmental, social, and economic aspects in order to better optimize effectiveness and benefits of environmentally friendly products, but also obtain knowledge about sustainable materials and product systems during design processes (Lee, Li, & Nam, 2016; Pahl & Beitz, 1996). Efforts by designers and/or manufacturers make it possible to eliminate chemical and hazardous materials (e.g., chlorine, lead, and polyvinyl chloride) in sustainable product development processes.

In the apparel industry, the cradle-to-cradle apparel design (C2CAD; Gam, Cao, Farr, & Heine, 2009) was adapted from the C2C design model (McDonough & Braungart, 2002) and apparel design and product development model (LaBat & Sokolowski, 1999; May-Plumlee &

Little, 1998). The C2CAD model uses the following four steps for new product design: (a) problem definition and research, (b) sample making, (c) solution development and collaboration, and (d) production. Application of this C2CAD model illustrates that the product, in the case of the cited research regrading a child's knitwear prototype, can be produced at an acceptable cost, demonstrate mechanically suitable performance, and yield strong performance in colorfastness.

The C2CAD model was also implemented in the application of design for disassembly of men's jackets to efficiently compost, reuse, or recycle the materials as the concept of design for disassembly (Gam, Cao, Bennett, Helmkamp, & Farr, 2011; McDonough & Braungart, 2002). To efficiently disassemble apparel products and to combat environmental pollution and resource depletion problems, Gam et al. (2011) suggested that apparel companies needed to build cooperative systems among retailers, consumers, and manufacturers as sustainability practices in the apparel and footwear industry. Although the C2CAD model is a useful and suitable model for creating sustainable apparel and apparel-related products, this conceptual model is not perfectly fit into the current study that is proposed here, especially the design, development and evaluation process of sustainable shoes, due to the complexity of the footwear design process as well as the requirement of physiological and physical wear tests of the product in a laboratory setting.

In this study, therefore, a new theoretical framework proposes for sustainable shoe development, design, and evaluation that integrates the functional-expressive-aesthetic (FEA) consumer need model (Lamb & Kallal, 1992) with the C2C design model (McDonough & Braungart, 2002) and wear test via human trials in a biomechanical approach. Some researchers have generated principles or standards that help guide those in the design industry in their development and assessment of sustainable products. Anastas and Zimmerman (2003) introduced the 12 principles of green engineering for scientists, engineers, and designers that suggest ways to optimize new products, materials, processes, and systems, as well as to enhance human health and natural systems in their own life-cycle stages. The application of the 12 principles recommends: (Principle 1) inherent rather than circumstantial substances, (Principle 2) prevention instead of treatment, (Principle 3) design for separation, (Principle 4) maximization of mass, energy, space, and time efficiency, (Principle 5) output-pulled versus input-pushed system, (Principle 6) conservation of complexity, (Principle 7) durability rather than immortality, (Principle 8) meeting of need, minimization of excess, (Principle 9) minimization of material diversity, (Principle 10) integration of local material and energy flows, (Principle 11) design for commercial after-life, and (Principle 12) creation of renewable products rather than depletion of resources. From the sustainable footwear material perspective, footwear designers can create and choose safe materials (Principle 1), and prevent a hazardous waste (Principle 2). By integrating commercial after-life processes (Principle 11) into aspects of sustainable design, footwear designers should and consider durability (Principle 7) and optimize products in designing closed-loop material flows (Principle 10). Therefore, this study adapted 12 principles of green engineering developed by Anastas and Zimmerman (2003) and incorporated the selected principles – 1, 2, 7, 10, and 11 – within the sustainable shoe development process. This integrated theoretical framework focuses on sustainable design and evaluation processes of sustainable shoe design and was used as a theoretical guide to conduct each stage of this study (see Figure 2.2).

Product Development Process Models

Product development is an important factor affecting success or failure in the apparel industry, which is ceaselessly changing according to consumers' needs and wants (Gaskill, 1992). Product development is applied to broad areas from engineering design (Lewis & Samuel, 1989; Glock & Kunz, 2005) and apparel industries (Gaskill, 1992; Regan, Kincade, & Sheldon,

1998) to academia (Dröge, Jayaram, & Vickery, 2000; Tyagi, Yang, & Verma, 2013). Specifically, engineering design processes include the following stages: (a) problem recognition, (b) problem definition, (c) exploration of problem, (d) search for alternatives, (e) evaluation and decision making, (f) specification of solution, and (g) communication of solution (Lewis & Samuel, 1989).

The product development process also deals with a sequence of stages, such as planning, design, creation, and marketing of rebranded or new products and services, to identify the implications of products (Tyagi, Choudhary, Cai, & Yang, 2015). The process converts conception of an idea into products for the development of a feasible solution (Medland, 1992). In general, the apparel design process model was developed by product engineers, architects, mathematicians, and design behavioral scientists working together (Regan et al., 1998).

Lamb and Kallal (1992) proposed a conceptual framework integrating functional, expressive, and aesthetic (FEA) consumer needs for apparel design intended for consumers with special needs. The target consumer is located in the core of this model surrounded by the cultural context. Designers can clearly understand target consumers' needs, wants, and information about physical and psychological characteristics, as well as cultural aspects, in order to solve a variety of design problems and to fully satisfy consumers' desires and requirements. Culture has the ability to greatly influence their behavior and decision-making as a mediator between target consumers and the FEA design criteria (Lamb & Kallal, 1992). Three-dimensions of FEA design criteria are positioned at the outer boundaries of the cultural context and each dimension is interrelated to each other with distinctive boundaries. Roles of each dimension are closely interwoven with the cultural context to comprehend the effect of the main elements on the product design process and development for wearable products (Kaiser, 1997).

The FEA consumer needs model has been incorporated in various steps of design processes for different product development process models (Hanks, Belliston, & Edwards, 1977; Koberg & Bagnall, 1981; Watkins, 1988). This model is one of the most commonly used design models, because of its specific focus on consumers and their product requirements (Bye & Hakala, 2005; Chea & Evenson, 2014; Chae & Schofield-Tomschin, 2010; LaBat & Sokolowsk; 1999; Lee, Damhorst, Lee, Kozar, & Martin, 2012; Pitimaneeyakul, LaBat, & DeLong, 2004; Regan et al.,1998).

Lamb and Kallal (1992) illustrated that the FEA model with design processes involves the following stages: (a) problem identification, (b) preliminary ideas, (c) design refinement, (d) prototype development, (e) evaluation, and (f) implementation. For example, Bye and Hakala (2005) designed a one-piece, female sailing suit incorporating the FEA elements into the design process developed by Watkins (1995). The criteria translated into garment attributes and were used in the development of a prototype garment and design features of the prototype. Chea and Evenson (2014) asked students to complete a group project for senior women's golf wear design using the FEA design criteria. The focus group interview helped the students understand the golf wear needs for senior consumers who played golf and identified significant design features such as support, fit, comfort, style, and a combination of feminine and athletic looks. As results of the study by Chea and Evenson (2014), students were able to understand consumers' perspectives and expectations about golf wear products. Furthermore, the FEA model has provided the educational teaching materials for instructors regarding how to create and evaluate diverse apparel and its related products. Ultimately, the FEA model is a useful tool for diverse stakeholders not only to enhance their creative problem-solving skills, but also to improve the end-users' prototype development.

Integrated Theoretical Framework

This study proposed an integrated theoretical framework adapted from the following theoretical elements: (a) the Cradle-to-Cradle (C2C) design model (McDonough & Braungart, 2002), (b) the Functional-Expressive-Aesthetic (FEA) consumer needs model (Lamb & Kallal, 1992), (c) sustainable apparel and product design processes (Cao et al., 2014b), and (d) 12 principles of green engineering developed by Anastas and Zimmerman (2003).

There are three main reasons why the proposed theoretical framework is appropriate for the sustainable shoe design process based on the C2C design framework. First, the proposed model for this study suggests three stages within the framework: (a) problem identification and eco-material selection, (b) prototype development and eco-material assessment, and (c) wear testing of shoes and product evaluation, compared with other sustainable apparel and products design processes (Cao et al., 2014b; Gam et al., 2011). Second, the integrated framework could be a useful teaching tool and valuable conceptual framework for exploratory research and an effective structure incorporated in FEA consumer needs for clothing design and evaluation (Lamb & Kallal, 1992; Romeo & Lee, 2016). Finally, detailed explanations of different segments (i.e., target market and consumer, culture, functional-expressive-aesthetic dimensions, cradle-to-cradle design process, and sustainable shoe design) and their relationships or interaction in the proposed framework are presented below.

Target Market and Consumers

As shown in Figure 2.1, at the core of the model, the eco-friendly target market and sustainable consumers, who are conscious of environmental impact and effect to their lives and health, prefer engaging in environmentally friendly behavior. Designers or shoe makers need not only to investigate current trends in the eco-friendly target market, but also to understand physical and/or psychological characteristics and demographics of potential consumers of sustainable products. Despite gender effect and difference of sustainable consumer behavior (Luchs & Mooradian, 2012; Zelezny, Chua, & Aldrich, 2000) and growth of men's footwear sales, little research has examined understanding with respect to sustainable shoes, more particularly from men's perspective and their acceptance. Target market of this study is a group of young consumers who are interested in sustainable men's dress shoes and wearable products.

Cultural Context

Culture encompasses the target market and consumers in the model. Luna and Gupta (2001) illustrated that culture plays a critical role as a mediator between a target market and consumer behavior. In our current dynamic global environment, an understanding of diverse cultural contexts is the key element of a successful international businesses (Chiu, Kwan, Li, Peng, & Peng, 2014). Due to a culture's direct and indirect influence on consumer behavior, it is crucial for designers and product developers to fully understand different cultural aspects and then consider cultural values and consumers' preferences for their product design and development. Zelezny et al. (2000) elucidated the cultural differences (e.g., Europe, Latin America, and the U.S.) has a great impact on environmental behavior than attitudes. Indeed, roles of each FEA dimension are closely related to cultural aspects to comprehend the effect of the main elements on the footwear design processes as well as wearable products (Kaiser, 1997). However, although sales or purchase intentions provide important challenges for sustainable footwear industry cross cultures, there were a small sample sizes (n = 42) for human trials and wearers' perceptions and acceptance of sustainable shoes in this experimental research. It is suggested that another survey could be conducted with a large sample population (n = 300) to validate our findings and cultural differences (Western and Eastern cultures) in the future research.

Functional-Expressive-Aesthetic Dimensions

At the third outer circle, the design criteria introduced by Lamb and Kallal (1992) consist of three sub-dimensions (function, expression, and aesthetics): (a) *functional aspect* – utility or functional information to measure footwear designs consisting of ease of mobility, fit, protection, and comfort. For example, usefulness of functional characteristics for apparel and products has led to developing special garments for hockey gear (Watkins, 1977), military clothing (Fourt & Hollies, 1970), wetsuits (Bye & Hakala, 2005), golf wear (Chea & Evenson, 2014), and tennis clothing (Jin & Black, 2012), (b) *expressive aspect* – symbolic meaning and communication of footwear equating values, roles, status, and self-esteem. For instance, apparel not only has the ability to help express a wearer's opinions/thoughts to others (Damhorst, 1990), but also embeds a symbolic meaning of a wearer's position or reputation as a uniform (Kaiser, 1997), and (c) *aesthetic aspect* – human desire for beauty to perform with respect to art, design, and relationship between materials and the body (Lamb & Kallal, 1992). Elements of fashion trends and/or designs for apparel influence color, style, pattern, and texture related to the standards of cultural attractiveness (Lamb & Kallal, 1992; Kaiser, 1997). In addition, each sub-dimension was interrelated to each other to fulfill the criteria for sustainable shoes proposed in this study.

Cradle-to-Cradle Design Process

All stages of the design process involve the cradle-to-cradle (C2C) design process with a zero waste approach (Anastas & Zimmerman, 2003; McDonough & Braungart, 2002) in the proposed theoretical framework. Materials made of eco-friendly materials (e.g., cotton fabric and hemp fabric, wood paper, and cork material) instead of chemicals and/or harmful materials (e.g., chlorine, rubber, synthetic fabric, and artificial leather), are utilized for developing sustainable shoes prototypes. Therefore, the creation of sustainable shoe design deeply considered simple pattern-making using a zero waste approach and using a recycled fabric in this study.

Stages of Sustainable Shoe Design

In this study, to make sustainable shoes, the C2C design process were carried out in the IsAcT design process for the sustainable footwear on three stages to: (a) identify problems and select eco-material, (b) assess eco-materials and create a prototype, and (c) test human trials and wearers' perceptions (see Figure 2.2).

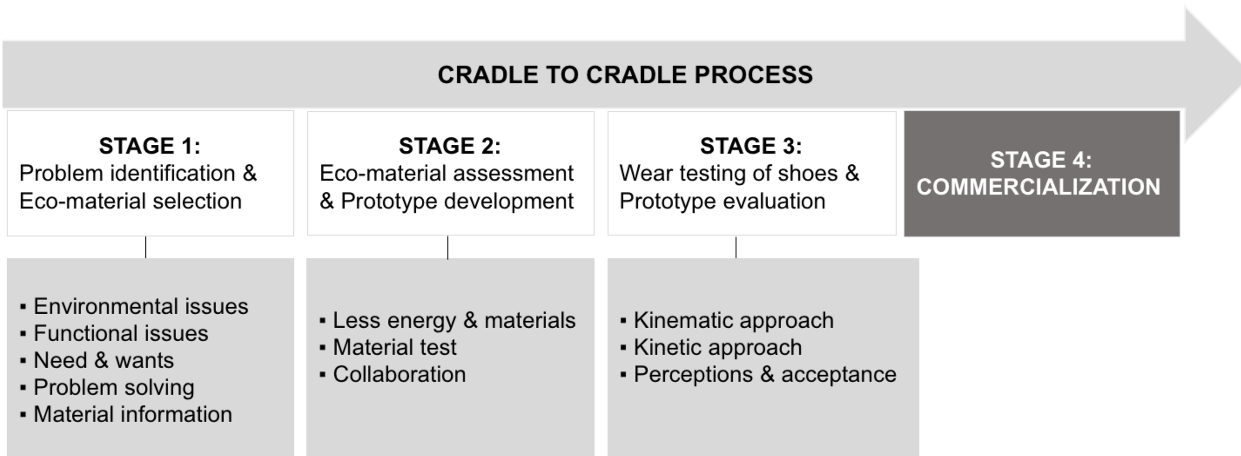


Figure 2.2. Sustainable shoe design process for the research project.

Stage 1. Problem identification and eco-material selection. This stage is aimed at helping designers to understand FEA consumer's needs based on Lamb and Kallal's (1992) study. Designers, in this stage, identify problems and investigate market trends. Products designed while incorporating the sustainability concept may encounter some concerns, due to discomfort, unfit, and limited amounts of information on materials for sustainable products and their sources (Cao et al., 2014b). Designers need to obtain a variety of knowledge, information, and resources about eco-materials (i.e., BC non-woven mat, denim fabric, hemp fabric, compressed paper, and cork material) chosen in the C2C approach incorporating safe materials (Principle 1) and less waste (Principle 2) (Anastas & Zimmerman, 2003; McDonough & Braungart, 2002). Designers and manufacturers should cooperate with each other to identify material problems and then choose eco-friendly materials that can meet all FEA needs. Thus, it is crucial for designers to determine materials that can lead to the production of creative, wearable, fashionable products (Braithwaite, 2014). To enhance the aesthetic appearance of the sustainable shoes, in this study, BC material, as entire outer shell of shoes, can be used to dyed with natural or recycling materials such as onionskin and leftover coffee grounds (Nam & Lee, 2016; Nam & Xiang, 2014).

Stage 2. Eco-material assessment and prototype development. After selecting suitable materials in Stage 1, collaborative approaches can help designers examine those materials' properties and then determine whether products are appropriate and eco-friendly and able to be produced without any chemical addition guided by the C2C design process. To achieve sustainable practices, designers and factories should integrate durability (Principle 7) and commercial after-life processes (Principle 11) into sustainable product design with natural materials, such closed-loop material flows, at the end of life use (Principle 10) (Anastas & Zimmerman, 2003; Gam et al., 2009). The second stage plays a crucial role in the footwear design process, because the selected eco-material assessment for a footwear prototype is related to wearers' comfort, mobility, acceptance, and perceptions of the prototype for the next stage 3.

Stage 3. Wear testing of shoes and prototype evaluation. To evaluate the products, focus/target groups were employed. Wear testing (kinetic and kinematic approaches) was conducted for the sustainable shoes' prototypes in this study. After finishing the testing, the focus groups evaluated the shoe's appearance and users' perceptions via survey based on the FEA consumer need criteria. Finally, designers determine whether the product is possible for commercialization (Cao et al., 2014a; Gam et al., 2009; Pitimaneeyakul et al., 2004).

Commercialization. Factory managers have concerns about sustainability practices (usages of utility, energy, air emission, water, and trash) in the production stage, as they attempt to minimize environmental impacts (Gam et al., 2009). Successful attainment of the study purpose within the proposed theoretical framework will allow the research to perform commercialization in the future, as in Stage 4. Commercialization, therefore, can offer potential for increasing consumers' satisfaction after enhancing comfort, fit, and styling for sustainable shoes as shown in Figure 2.3.

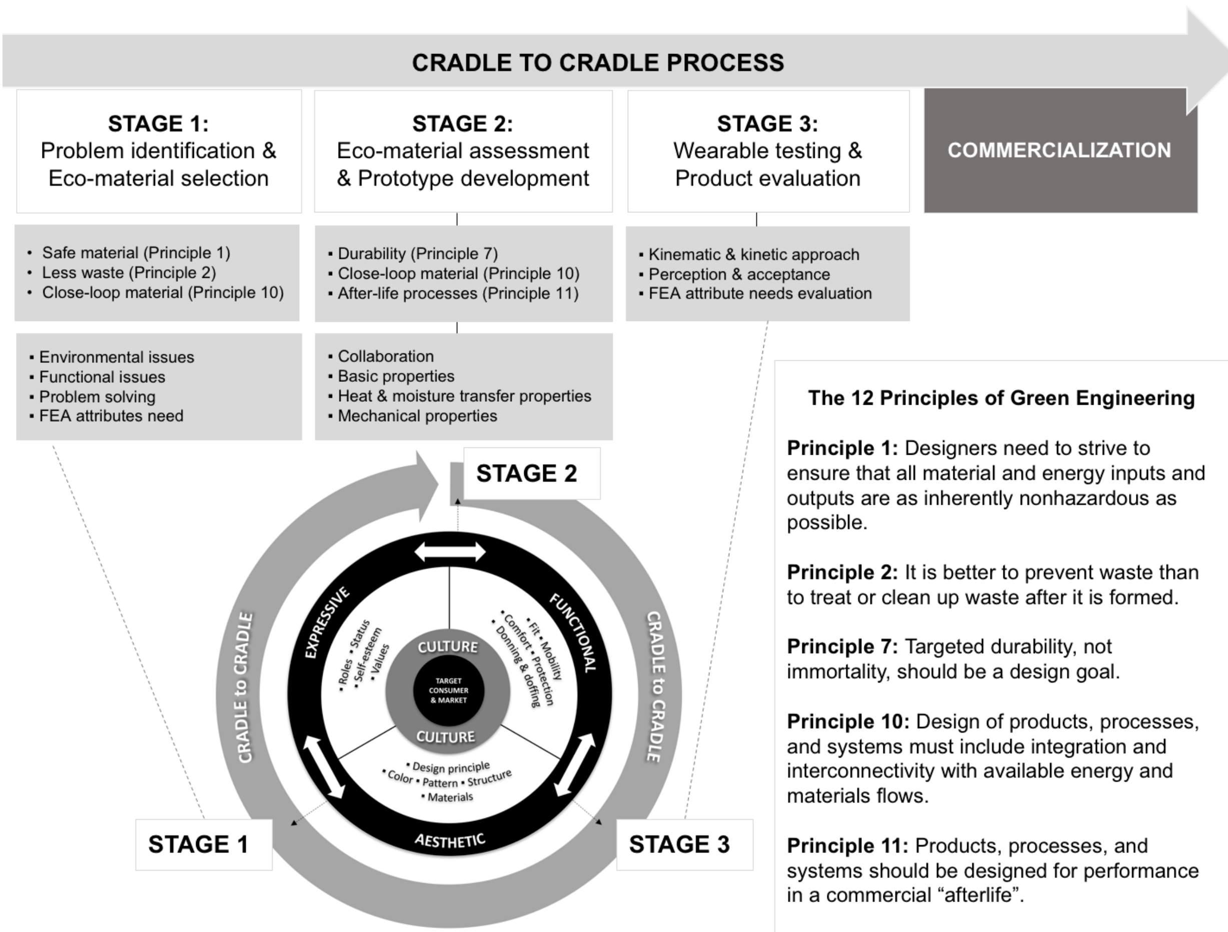


Figure 2.3. The proposed integrated theoretical framework created by researcher.
Note. This framework modified form Anastas and Zimmerman (2003); Cao et al., (2014b); Lamb and Kallal (1992); McDonough and Braungart (2002).

In sum, the proposed integrated theoretical framework, combining the FEA consumer's needs model and C2C design process model integrated five principles (1, 2, 7, 10, and 11), is a feasible design framework for developing a sustainable footwear (product development) design and process. Ultimately, this framework enables designers and manufacturers to understand the target consumers' needs, to enhance awareness of environmental issues, and to urge them to easily and fully implement sustainability practices into new sustainable product design and development process from either biological or technical nutrients and become alternate future means, which help the footwear industry fully shift into the C2C approach.

Sustainable Materials and Properties in Sustainable Shoes

Using the C2C approach (McDonough & Braungart, 2002), there are a wealth of fashionable leather alternatives that enable sustainable and creative design processes in footwear production (Braithwaite, 2014). The development of renewable resources (e.g., carbon hydrate, lignin, oil, and protein) alleviates resource depletion and is a vital aspect of sustainability practices in the footwear industry.

Many researchers have developed bio-based composite materials using chicken feather fibers (Cao et al., 2014b; Huda & Yang, 2009; Zhan, Wool, & Xiao, 2011), soy bean-based protein fibers (Hong & Wool, 2005), and cellulosic fibers (Chen, Shin, & Jiang, 2018; Lee et al., 2014). Cao et al. (2014b) developed eco-friendly apparel and footwear products using bio-based materials and revealed the great potential of the materials to be used in making wearable, functional, and useful products; however, they did not explicitly provide the details on testing the bio-based materials' properties (e.g., thermal comfort, mechanics, and wettability). Several academic studies (e.g., Chen et al., 2018; Lee et al., 2014) have been conducted to develop a renewable material (e.g., cellulosic fiber mat) as a leather alternate, striving to create one that is biodegradable and compostable without contributing to landfills. Lee et al. (2014) identified an optimal way for growing and combining cellulosic fibers with sustainable biopolymers to reduce moisture regain and to increase the strength of the cellulosic fiber, which leads this material to be used in wearable products as a leather alternative material. Such research points to promise sustainable materials that are alternatives to leather in the footwear industry.

Bacterial Cellulosic Non-Woven Mat

Bacterial cellulosic (BC) is one material that has demonstrated valuable properties, such as its unique structure, biodegradability, mechanical strength, and high crystallinity (Dayal & Catchmark, 2016; Esa, Tasirin, & Rahman, 2014; Qiu & Netravali, 2012). In spite of the wide uses of BC non-woven mat in a variety of industries (bio-medical, textile, and food), without any additional reinforced material (Qiu & Netravali, 2012), the BC alone still lacks the durability required of daily usage in a fully performing sustainable application (Esa et al., 2014; Lee et al., 2014). Green tea-based BC non-woven mats, however, proved to be unique and stiff in ways that are similar to leather (Lee et al., 2016), while the material was also considered to be wearable, versatile, and practical for apparel and footwear. These collective results indicate cellulosic fibers as one possible alternative for traditional materials such as leather. The growing attention to environmental consequence and awareness of environmental concerns and safety, thus, have been reflected in the increasing development of natural or bio-based materials (Baptista, Ferreira, & Borges, 2013).

Fashion designer, Suzanne Lee introduced the notion of “grow your own clothes” using a kombucha-based BC non-woven mats (Llanos, 2012), but did not fully consider the wearability of this BC non-woven mat in various weather conditions (e.g., rainy and snow days). Development and optimization of the BC non-woven mats were achieved by Lee et al. (2014) using the following combination of natural ingredients with commercial organic SCOBY (Symbiotic Colony of Bacteria and Yeast). A few research presented sustainable products such as vest (Lee et al., 2014), baby shoes (Lee & Nam, 2015), and male and female shoes (Nam & Lee, 2016) was designed using the BC non-woven mats. Lee et al. (2014) examined this material’s properties and reported one major issue with regard to easy moisture absorption from the atmosphere or human body, which results in a softening of the material and a loss of tensile strength. This implies that a single layer of BC non-woven mat may not be effective for use as a leather alternative material in the footwear industry. Given the potential benefits, the BC material should be explored as an innovative way to develop a multi-layered cellulosic material for the entire shell of sustainable shoes with both upper and inner parts to enhance the overall strength as well as comfort for the wearers.

Fashionable style design with dyed and colorful bio-based materials for footwear are more attractive to young consumers rather than apparel (Cao et al., 2014b). The natural dyeing process of the cellulosic fiber can provide an attractive alternative to synthetic dyeing processes, due to there being no issue with disposal or reduced toxicity, and enhanced cost effectiveness (Gulrajani, 2001; Nam & Xiang, 2014; Samantaa & Agarwal, 2009). The green-tea based cellulosic fiber mats, produced through natural dyeing methods using the leftover coffee grounds and red onion skins, a process enabling the recycling of food wastes, can yield natural colors for an aesthetically appealing footwear design (Nam & Lee 2016).

Denim Fabric (Twill Weave)

Denim is “a yarn-dyed cotton twill available in different weights or in interlacing patterns” (Kadolph, 2010, p. 282). Denim, a cotton twill weave with indigo dyed warp-yarn and white weft-yean, is the most popular fabric in the apparel industry, due to its sturdy and flexible texture (Kan, 2014; Paul, 2015). Recently, manufacturers have investigated developing dynamic and innovate textile products (e.g., sofa, bag, shoes, and covers) using denim with a variety of finishing applications to incorporate sustainability elements and improve the comfort level of the fabric (Kadem & Saraç, 2017; Khalil, 2015). According to the United States Environmental Protection Agency (EPA), more than 13 million tons of textiles (at least 85% of apparel) are thrown away every year (Frazee, 2016). To repurpose such waste, worn jeans made from denim could be utilized as a pattern-making material for sustainable shoe design. In addition, because denim fabric may play an important role as a reinforcing material (Kumar, Chatterjee, Padhye, & Nayak, 2016), in this study, it was used to bond the BC non-woven mat and hemp fabric in developing a multi-layered material to enhance tensile strength for sustainable footwear.

Hemp Fabric (Plain Weave)

A fabric made of hemp, fiber, and seed parts from Cannabis sativa is coarser and stiffer than most other materials used as sustainable alternatives to conventional materials (Kadolph, 2010). A plain woven fabric made from hemp was used in this study. Hemp is one green composite of many (e.g., bamboo, cork, and ambary) which are fully degradable and sustainably derived from trees and plants (Ochi, 2006; Takemura & Minekage, 2007). In general, hemp, which grows rapidly in the field without the use of pesticides, can be produced at a reasonable price and is a valuable natural material in the market (Caba, 2015; Takemura & Minekage, 2007). Hemp plain weave fabric provides several unique benefits for those who wear products made of this material: (a) excellent perspiration, (b) natural hygiene, (c) anti-statistic nature, (d) resistance to mold and mildew, and (e) resistance to ultraviolet radiation (Stankovic & Bizjak, 2014). The material, therefore, holds the possibility of being used in various products such as food, personal care, and clothing (Caba, 2015). The tensile property of hemp fabric demonstrates the effective reinforcement of green composites (Takemura & Minekage, 2007), which provides enormous possibilities for use as a durable, alternative material in apparel and footwear production. Due to these specific characteristics and benefits of hemp fabric, in this study, the inner part of a multi-layered material in the sustainable shoes included this hemp fabric.

Cork Material

One of the environmentally friendly renewable bark is a cork material from an oak tree (Shinde, Tate, Shinde, Kadam, & Patil, 2016). The versatile properties (e.g., light weight, strong, elastic, flexible, thermal insulation, sound absorption) of cork are high performing and undergo multiple applications, such as used as stoppers (Shinde et al., 2016), footbeds (Means, 2015), and fashion apparel, like in shoes, clothing, handbags, and accessories (Italie, 2014). Footwear using a cork material has the capability to maintain wearers' comfort, improve balance and posture, and provide healthy walking for human feet (Means, 2015). Due to less joint stress and less of a shock impact during walking, the shoes are not only comfortable underfoot, but throughout the body (Means, 2015). As a moisture-wicking material, a cork insole can naturally minimize plantar fasciitis pain, and remove odor left on the inside of shoes (Lipscomb, N/A; Musante, 2014). In this study, the outsole of the shoes was made from cork. Thus, as discussed so far, the materials of green tea based BC nonwoven mats, denim twill weave fabrics, hemp plain weave fabrics, and cork materials were used for the sustainable shoes prototype in this study.

Thermal Comfort of Material Properties

The interaction of materials' properties with wearers' senses contributes to physical comfort and is related to physical stress during human performance (Slater, 1996; Wen, 2014), depending on the work intensity, material composition, and thermal environment. Major factors contributing to thermal comfort are the heat and moisture transfer properties of a clothing system (McCullough, Huang, & Kim, 2004). The wearable products' comfort can be predicted through the weight, thickness, air permeability, thermal resistance, and water vapor resistance of the material (Lee & Obendorf, 2007; Slater, 1996), especially because of its relationship with wearers' fatigue and discomfort (Wen, 2014).

Fiber composition, fabric structure, and air permeability can also influence thermal comfort when controlling for the same thickness and weight of fabrics (Yoo & Barker, 2005). Lightweight and thin fabrics, thus, can be effectively used for protective and functional footwear. The fabric structure and style of a wearable product influence its air permeability, as air passes through the pores in the fabric and the opening of the product, generating air flow (Wen, 2014).

For example, materials in chemical protective clothing are air impermeable, while those in summer sportswear are required to be air permeable. These aspects make it important to consider materials' composition, structure, and performance to determine the fabric appropriateness for footwear design, development, and production. It is also crucial to empirically analyze the components of comfort and functionality for each potential material to be used in footwear design and development.

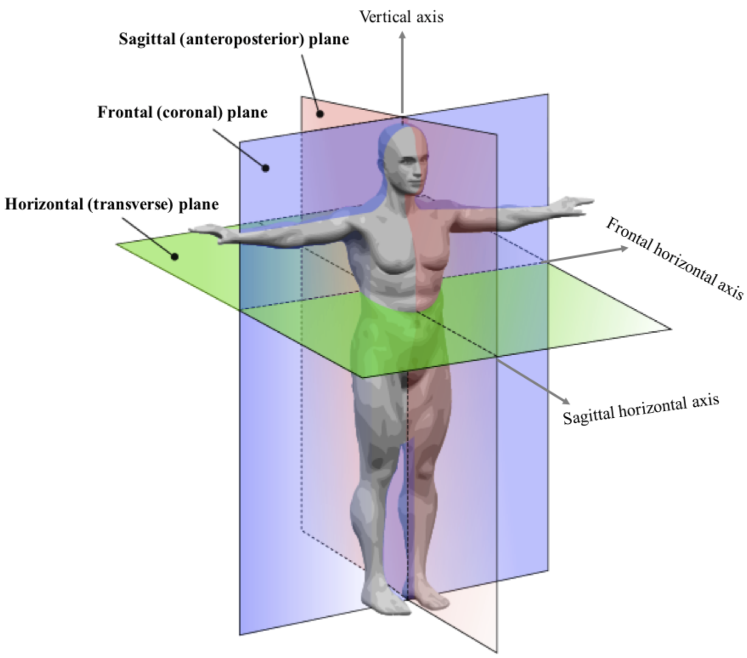
Material weight and thickness frequently promotes physical stress on the wearer, due to the discomfort of wearing a product associated with the mechanical properties (e.g., tensile strength, elongation; Wen, 2014). Adding multi-layered fabrics and increasing thickness not only make it significantly difficult for wearers to perform their tasks, but also decrease air and moisture transfer for total heat loss (McQuerry, DenHartog, & Barker, 2017; Rossi, 2005). A multi-layered composite system could be considered as a layering structure for functional clothing (Gonzalez, Endrusick, & Levell, 1998) and footwear to create resistance to both sensible and insensible heat fluxes affecting heat balance in the product, because the total insulation of this multi-layered material is greater than that of the single-layered material (McQuerry et al., 2017). In general, natural fibers are less compatible with the hydrophobicity, less uniform, and contain poor thermal stability, due to variation in climatic conditions (Carrillo, Colom, & Canavate, 2010). The surface of natural fibers needs to be modified or pretreated in order to increase the waterproof capabilities and to decrease surface roughness, resulting in a composite with better mechanical properties (Kalia, Kaith, & Kaur, 2009; Mwaikambo & Ansell, 2002). Li, Tabil, and Panigrahi (2007) stressed that high tensile strength, high durability, low density, good moldability, and recyclability are necessary for properties of natural fibers and should be considered when selecting suitable materials in the footwear design and development. As a result, diverse samples of bio-based composites have been manufactured in accordance with renewable polymers and their properties (Liu, Misra, Askeland, Drzal, & Mohanty, 2005; Mohanty et al., 2005).

The wettability of materials is another important factor on thermal comfort, because the water-absorbing behavior, water-holding capacity, and drying time influence wearers' feeling of dampness or wetness in a fabric (Kalia et al., 2009; Yuan & Lee, 2013). Consequently, optimal configuration and better understanding of a multi-layered material's properties can serve unique purposes in footwear design and development, as well as enhancing wearers' thermal comfort, and are considerations we took into account in this study.

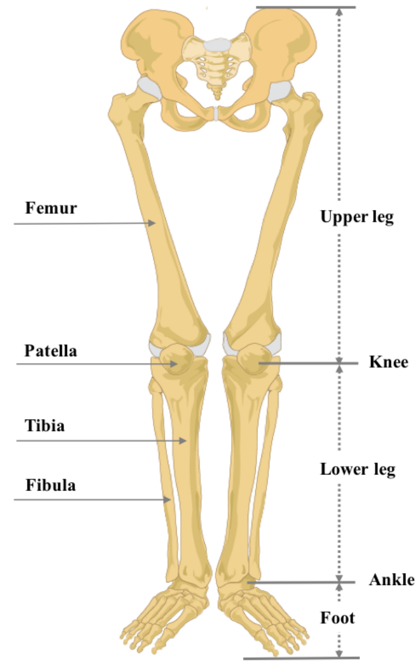
In sum, understanding properties of eco-materials is important for sustainable shoe designers and manufacturers. The designers consider materials' characteristics and touch feeling (e.g., wearer's physical differences) to make comfort and suitable fit for sustainable footwear.

Structures and Movements of Lower Extremity

The human movement in a plane occurs about axis of rotation perpendicular to the plane (See Figure 2.4A). A plane is a flat, two-dimensional surface about an axis, a straight line around which an object rotates. In order to exactly identify human motion, a three-dimensional analysis is necessary (Oatis, 2009). Based on a system of planes and axes, in the human body, there are three cardinal planes about three axes: flexion and extension in the sagittal (anteroposterior) plane about a frontal horizon axis, abduction and adduction in the frontal (coronal/ lateral) plane about a sagittal horizontal axis, and internal and external rotation in the horizontal (transverse) plane about a vertical axis (Behnke, 2012; Hamill, Knutzen, & Derrick, 2013; My-MS.org, N/A).



A. Three planes and axes



B. Bones and joints of the lower extremities

Figure 2.4. Three planes and axes and anatomy of the lower extremities.
Note. Modified and adapted from "My-MS.org" and linked to https://my-ms.org/mri_planes.htm and "New Health Advisor" and linked to https://www.newhealthadvisor.com/lower-extremity-anatomy.html respectively.

The human leg commonly referred to as the lower limb (extremity) of the body, consists of a total of 62 bones, including hip, leg, ankle, and foot. As shown in Figure 2.4B, the bones of the leg are four major bones such as femur, patella, tibia, and fibula (Matshes, Burbride, Sher, Mohamed, & Juurlink, 2005; New Health Advisor, N/A). The bones of the lower limb are adapted for bipedal locomotion. The lower extremity is made up of five distinctive segments: (a) the upper leg – the strongest and leanest muscle extending from the hip to the knee, (b) the knee – a pivot-like hinge joint, connecting the bones in the upper and lower leg, (c) the lower leg – controlling foot movement, including the tibia and fibula, (d) the ankle – enabling rotating and flexing in foot-movement and balance, and (e) the foot – stronger and less moveable, a complex structure like a hand (Behnke, 2012; Health Line Medical Team, 2015). The lower extremity consists of major 28 muscles, deeper muscles, and ligaments interacted with each movement in human gait as illustrated in Figure 2.5. The hip joint is classified as a triaxial joint, having movement in three planes in terms of three axes. The musculature that generates those six fundamental movements includes flexors, extensors, abductor, adductors, and rotators. The muscles of the hip joint and upper leg are grouped by position as anterior, posterior, lateral, or medial to the hip joint (Behnke, 2012): (a) *Anterior muscles* – ilopsoas, psoas major, iliacus, psoas minor, sartorius, rectus femoris, tensor fasciate latae, pectieus, (b) *Posterior muscles* – biceps femoris, gluteus maximus, piriformis, semitendinosus, seminmembranosus, gemellus superior, internal obturator, genellus inferior, external obturator, quadratus femoris, (c) *Medial muscles* – adductor longus, adductor brevis, adductor magnus, gracilis, and (d) *Lateral muscles* – gluteus medius, gluterus minimus.

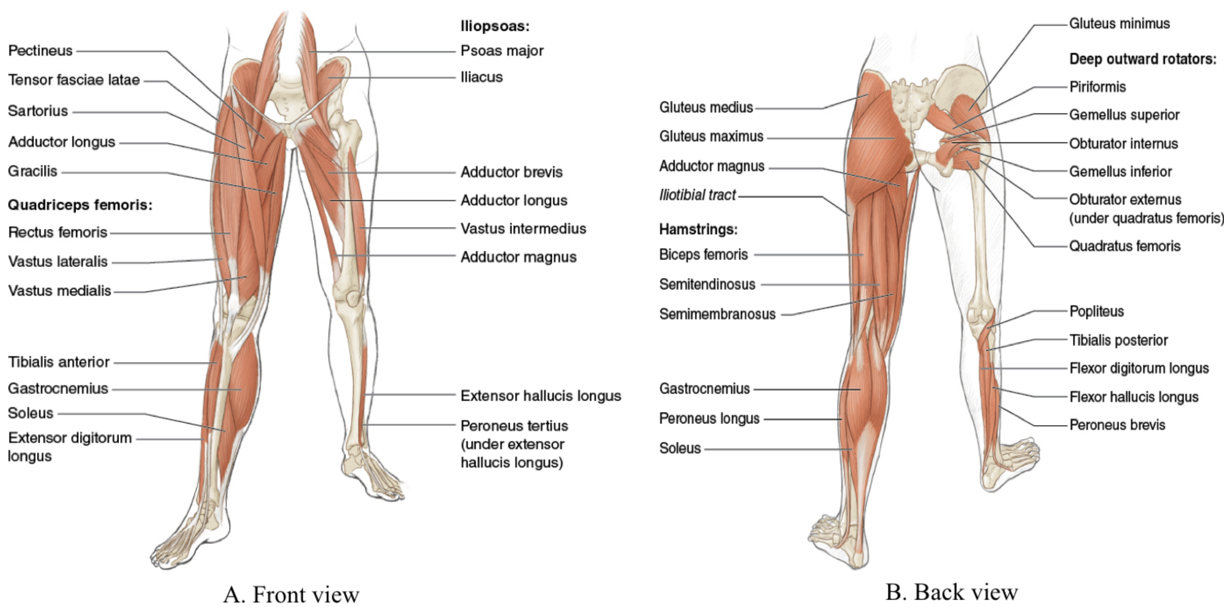


Figure 2.5. Main muscles of the lower extremities.
Note. Modified and adapted from "Pilates Anatomy by Isacowitz and Clippinger (2011) and linked to https://doctorlib.info/yoga/pilates/4.html

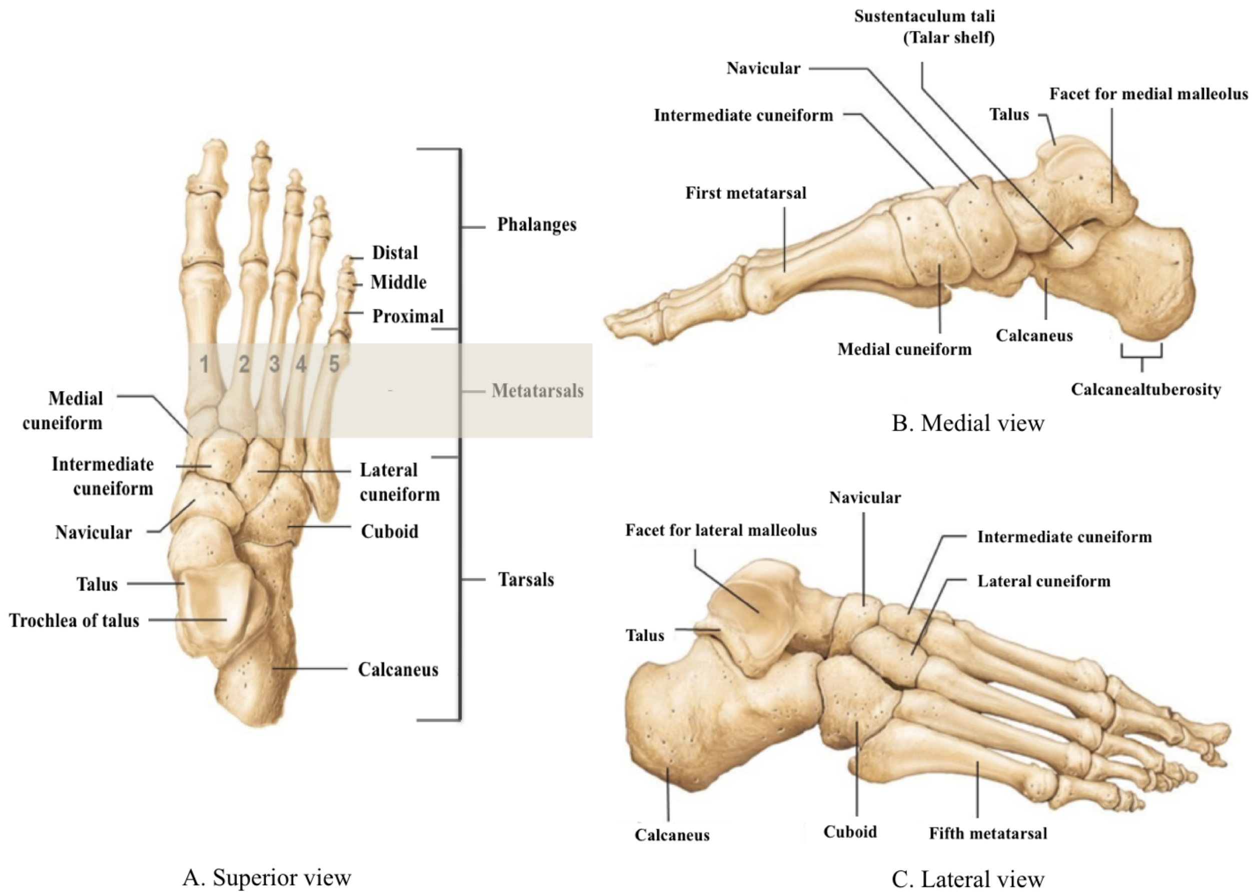


Figure 2.6. Tarsal and foot bone anatomy.
Note. Modified and adapted from Talus, cuboid bone, navicular bone of the foot by anatomy note (2018) and linked to https://www.anatomynote.com/human-anatomy/extremity-anatomy/talus-cuboid-bone-navicular-bone-of-the-foot/

Furthermore, the muscles of the knee and lower leg are generally divided into two major muscles such as anterior muscles and posterior muscles. The muscles of the lower leg, ankle, and foot are typically divided into extrinsic and intrinsic muscles (Behnke, 2012; Isacowitz & Clippinger, 2011).

In superior view there are several bones: distal phalange, middle phalanges, proximal phalanges, five metatarsals, lateral cuneiform, cuboid, intermediate cuneiform, navicular, talus, and trochlea bones bones. The medial view presents a variety of bones: medial malleolus, talus, sustentaculum tali, calcaneal tuberosity, calcaneus, medial cuneiform, first metatarsal, intermediate cuneiform, and navicular bones. In lateral view there are a diversity of bones:

intermediate cuneiform, lateral cuneiform, fifth metatarsal, cuboid, calcaneus, the facet of lateral malleolus, and navicular bones.

The bones, joints, muscles, and tendons of the human foot, working together consist of the most complex mechanical structure in the human body (Vass & Molnár, 2006). The lower limbs support the human body while the sole of the foot simultaneously leads to elaborate internal adjustments (Health Line Medical Team, 2015). Therefore, the legs facilitate walking, running, jumping, and other movements for individuals' daily life.

The kinematic body movements lead to vary combinations in the joint of human body. The eight fundamental movements (flexion, extension, abduction, adduction, rotation, inversion, eversion, and circumduction) are found in lower extremity (see Table 2.1 and Figure 2.7).

Table 2.1. *Segment Joint Movements of Lower Extremities*

Segments	Joints	Movements
Thigh	Hip	flexion, extension, hyperextension, abduction, adduction, hyperadduction, horizontal adduction, horizontal abduction, med/lateral rotation, circumduction
Shank	Knee	flexion, extension, hyperadduction, med/lateral rotation
Foot	Ankle	plantarflexion, dorsiflexion
	Inter tarsal	inversion, eversion
Toe	Metatarsophalangeal	flexion, extension, abduction, adduction, circumduction
	Interphalangeal	flexion, extension

Flexion and extension generate most movable joints (including the toe, ankle, knee, hip, trunk, shoulder, elbow, wrist, and finger) in human body (Hamill et al., 2013). *Flexion* exists as a bending movement associated with angle of the joint between two adjacent segments decreases (e.g., thigh, shank, foot, and toe in lower extremity), and moving over the normal range of flexion (called hyperflexion). On the other hand, *extension* exists as a straightening movement related to angle of the joint between two adjacent segments increase as the joint returns to the zero or reference position (e.g., thigh, shank, foot, and toes in lower extremity), and extending movement (called hyperextension). In addition, plantarflextion (movement of the bottom of the foot down towards the leg that increase the relative angel between the leg and the foot) and dorsiflexion (movement of the foot up towards the leg that decrease the relative angle between the leg and the foot) occur in foot flexion and extension.

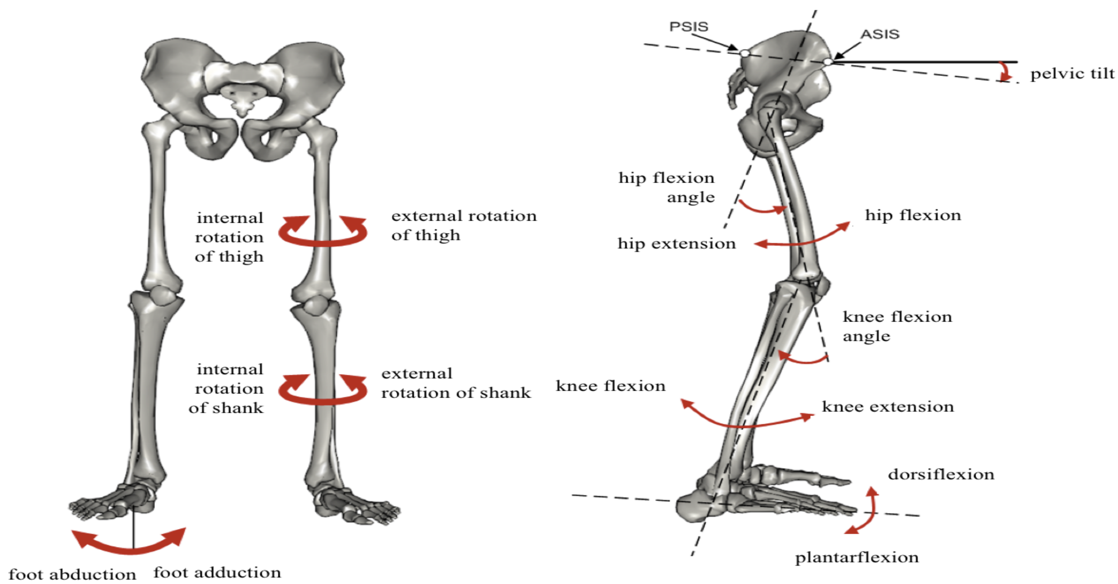


Figure 2.7. Movements of lower extremities.
Note. Adapted from Vicon documentation liked to https://docs.vicon.com/display/Nexus25/Plug-in+Gait+kinematic+variables

Abduction is a movement away from the midline of the body or the segment (e.g., thigh and toe in lower extremity), and moving more than 180° (called hyperabdduction). *Adduction* is the return movement of the segment (e.g., thigh and toe in lower extremity), and moving over the normal range of adduction (called hyperadduction). *Rotations* are movement of right and left segment in terms of a vertical axis (e.g., thigh and shank in lower extremity) and can divide medial (internal) and/or lateral (external) rotation. In the foot, inversion and eversion exist in the inter tarsal and metatarsal articulations. At anterior posterior axis, *inversion* leads to the medial border of the foot lifts so that the sole of the foot faced medially toward the other foot while *eversion* is the opposite movement of the foot. *Circumduction* occurs in any joint or segment (e.g., thigh and toe in lower extremity) that can be moved in conic fashion as the end of the segment moves in a circular path (Hamill et al., 2013).

Foot Morphology

Since the 18th century, the footwear industry has provided a standardized measure for shoes (Vass & Molnár, 2006). Due to different shoe-size systems and units of measurements used worldwide, each country/region takes standards of different shoe sizes into account. In the American shoes size system, the scale starts one-twelfth of an inch from the metric system, suitable for measuring the length of foot or shoes (Vass & Molnár, 2006). Each shoe brand, even within the same country, also may slightly differ their own shoes sizes from the standard chart.

Human foot is a biomechanically complex anatomic structure that offers to distribute weight of the human body. Foot morphology refers to form and structures, including length, width, and arch types of foot. It is hard for footwear industry to exactly accommodate fit and sizing of footwear, due to of consumer's variations such as foot size, arch, toe shape, age, gender, weight, and walking speed (Moore et al., 2013; Oatis, 2009).

Foot size is measured by the length of the foot from heel to the tip of the big toe, as well as the width of the foot across the widest part of the foot when shoemakers or designers create new shoes. Based on the foot size, traditionally shoemakers use a shoe last which measures around last with a flexible tape; toe spring; ball girth; waist girth; instep girth; long heel girth; short heel girth; heel lift; and stick length (see Figure 2.8).

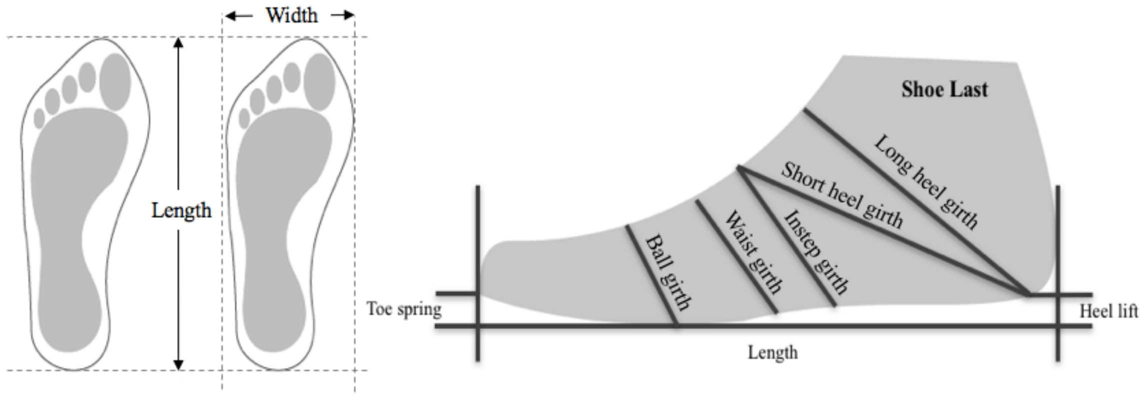


Figure 2.8. Measuring the foot size using last created by the researcher.

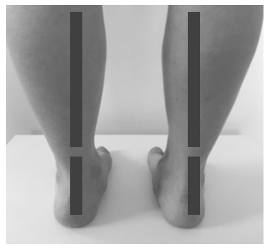
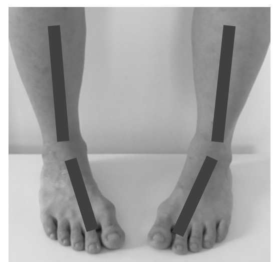
As shown in Table 2.2, American adult shoes sizes present a wide range from 6 to 15 in men's sizes which can covert to inch, millimeters (e.g., South Korea), and centimeters (e.g., Japan) used footwear industry in Asian countries. The Statistic Brain Research Institute (2015) reported that the average range of men's shoe size globally is from 9 to 12 US metric system-based shoes size. Male adult average shoes size is 10.5 in the United States. Therefore, it is difficult for consumers to purchase a pair of shoes online without trying on the footwear.

Table 2.2. *Men's Shoe Size Chart*

Men's Shoe Sizes												
U.S.	6	7	8	9	9.5	10	10.5	11	12	13	14	15
inch	9.3	9.8	10.1	10.3	10.5	10.6	10.8	11	11.3	11.6	11.9	12.2
mm	240	250	260	270	275	280	285	290	300	310	320	330
cm	24	25	26	27	27.5	28	28.5	29	30	31	32	33
				Global average size ranges								

As shown in Table 2.3, There are three main shapes of toes (Vass & Molnár, 2006): Egyptian (ordered toes), Greek (longest second toe), and Roman (at least three toes the same length). In addition, human feet can generally be divided into three different shapes depending on the foot arch types: (a) healthy (normal) foot, (b) flatfoot, and (c) club (high) foot.

Table 2.3. *Effect of Arch on Shoes and Toe Shapes*

		Effect of Arch on Shoes		
Toe shape	Arches	Alignment	Orthotic	Outsole
 Egyptian	 Normal	 	Stability: *healthy*	
 Greek	 High	 	Cushion: *supination unhealthy*	
 Roman	 Flat	 	Motion control: *Pronation unhealthy*	

Note. This table created by the researcher.

The three foot arches are briefly explained in the following:

(1) Normal arch: Approximately 40% of the population has a normal arch. The pronation and supination occur appropriately during the gait cycle. A neutral gait refers to efficient biomechanics for the foot, leg, and body movement.

(2) High arch: The supination is a natural and normal part of movement. However, supination can become harmful when it occurs for too long a time when walking and running. Excessive supination, also called under-pronation, is not a common foot type. This causes excess

strain on the ankle muscles and tendons and decreases ankle flex, reducing the foot's natural ability to absorb shock.

(3) Flat arch: Overpronation refers to when the arches flex too far inward or stay collapsed for too long and pronation is considered excessive. Overpronation, a common foot type, can lead to a negative influence on the whole human body's alignment. In addition, people of advanced age, those who are overweight, and those who stand at work or do extreme exercises more readily experience overpronation. Feet and ankles experiencing severe overpronation can rotate too far inward simply during standing.

Materials for Footwear

Materials used in footwear are not only required as a part of inherent and necessary performance and the comfort of shoes, but are also associated with the aesthetic and utility aspects for footwear design. Traditionally, certain materials (e.g., leather, rubber, adhesives, polyurethane, and polyvinyl chloride), are commonly used in the footwear industry (Intertek, 2011). Depending on use and performance of the footwear, each material can produce different types and designs of shoes such as dress shoes, military boots, rain boots, sneakers, slippers, and active shoes (Intertek, 2011; Motawi, 2015).

In general, leather shoes are made of synthetic, genuine, or real leather (e.g., calf, pig, goat, and horse skins) which can not only be flexible, shapeable, and based-protein, but also absorb and transport perspiration (Motawi, 2015; O'Keeffe, 2012). The upper shell of leather shoes is smoothed, due to natural capability of the leather to apply to a shape of the shoes (O'Keeffe, 2012). Depending on types and thickness of leathers, leather shoes is designed using a shoe last (a foot shape) made of a wooden or plastic form (Motawi, 2015), while synthetic leather is commonly used for footwear as well, because it is less expensive despite of less moisture resistant and perspiration. As shown in Figure 2.9, leather shoe components that encase the foot basically consist of three major parts: (a) outer shell including upper or vamp shell (wrapping dorsum of foot), toe box (encompassing toes), backstay or heel cap (covering around calcaneus), quarter (contacting between midfoot and calcaneus), and tongue (underlying shoe lacings), (b) inner shell (directly contacting to sock or foot skin), and (c) soles (interfacing between plantar aspect of foot and ground), including insole, midsole, and outsole. The materials carry out aesthetic and functional aspects of the shoes (Braithwaite, 2014). Men's dress shoes have simpler component than running (athletic) shoes for design approach and methods of making shoes.

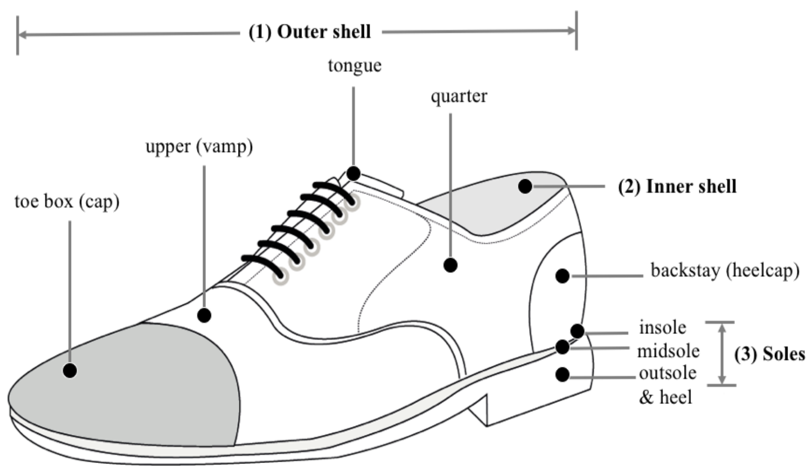


Figure 2.9. Structures of men's leather shoes created by the researcher.

The entire pipeline of footwear design and development, from material selection to footwear production, can have massive negative impacts on the environment (e.g., air and water pollution and natural resource exhaustion); thus, the selection of sustainable materials is an important initial step for those seeking sustainability practices in the footwear production process. The most fundamental and commonly used material for men's dress shoes is leather, because of its durable, flexible, stretchable, and stylish characteristics and functions (Motawi, 2015). However, leather tanning processes, involving pre-tanning, tanning, and post-tanning, lead to huge amounts of used water and disposal wastes, restricted cost efficiency, and workers' health issues (Habib et al., 2015; Suresh et al., 2001). These problems motivate footwear producers to reconsider using leather as the fundamental material for footwear in light of its negative impacts on workers' health and environment. Furthermore, some populations in the local and world environment, as well as in workplaces, have caused footwear manufacturing workers to be hurt or killed, especially in the leather and tanning industry, mostly from a hazardous powder or gas (e.g., chromium) produced from the chemicals, feed, water, energy, and waste, subsequently contributing to workers' health problems (e.g., cancer, aplastic anemia, and leukemia), and producing disadvantages of eco-efficiency on our plants. (Intertek, 2011; Tarantola, 2014). Moreover, according to the United States EPA, livestock pollution and excrement is extremely hurtful to nature. Products made of leather (e.g., shoes, jackets, car seats, belts, wallets, and home furnishing) are the largest cost global product accounting for $47 billion over 60% of the trade between 2009 and 2010 (Tarantola, 2014). With the wealth of fashionable leather alternatives, for example, the materials enable the sustainable or creative design process in footwear within the C2C approach (Braithwaite, 2014; McDonough & Braungart, 2002).

Although previous researchers have investigated bio-based composite materials are possible to use making wearable, functional, and useful products (Baron & Schmit, 2005; Cao et al., 2014b; Cheng et al., 2009; Hong & Wool, 2005; Huda & Yang, 2009; Zhan et al., 2011), they did not explicitly provide any specific description of the design process or the prototypes using the bio-based materials. In this study, the green tea-based BC material, used as a leather alternate, its properties, and the design process were documented within the C2C design, which will prompt future designers and researchers to consider this BC material as one potential sustainable resources for sustainable product design.

Gait Analysis for Quantitative Evaluation of Footwear

The cycle composing the sequential and rhythmic body movement of walking is called the "gait cycle," a term applied to describe the simplest form of human locomotion in a forward progression (Kale, Cuntoor, Yegnanarayana, Rajagopalan, & Chellappa, 2003). The gait cycle refers to cyclical movement that is the interval between two continued occurrences of one of the repetitive events of walking (Neumann, 2013). This means that the preference (dominant) foot (e.g., right or left foot) attaches to the ground and completes the cycle when the same foot (e.g., right or left foot) contacts the ground again. In general, the gait cycle is divided into two major phases: stance (60%) and swing (40%). Characteristics of the basic functional tasks of the swing and stance phase of gait provide a framework for characterizing the movements in each phase of the gait (Oatis, 2009; Whittle, 2014).

As illustrated in Figure 2.10, there are eight major events during a gait cycle: (a) initial contact (0%) – starting point, (b) opposite toe off (0-10%) – the toe comes down towards the ground with both heel and toe on the ground, (c) heel rise (10-30%) – the body advances over the stationary foot, (d) opposite initial contact (30-50%) – the heel starts to rise from the ground and the toe pushes off from the ground to propel the body weight to move forward, (e) toe off (50-60%) – ends when the foot leaves the ground, with the toe being the last point of contact with the ground, (f) feet adjacent (60-73%) – the toe completely leaves the ground, (g) tibia vertical (73-87%) – the forward advancement of the accelerated limb, and (h) next initial contact (87-100%) – the limb advancement is completed and before the heel strikes, the cycle gait ends, marking the beginning of the next cycle (Neumann, 2013).

The purpose of gait analysis is to conduct quantitative evaluation and interpret the movement, joint motion, and force of humans and animals to diagnose and rehabilitate orthopedic problems in the lower extremity by identifying abnormal working patterns of joints and muscles (Cappozzo, 1984; Davis et al., 1991). Mobility analysis is carried out for incorporating movement of human body segments with interactions between internal and external forces (Cappozzo, Figura, Marchetti, & Pedotti, 1976). With respect to biomechanics, human locomotion is an extremely complex phenomenon systematically associated with a number of musculoskeletal systems and functions through a multidisciplinary approach (Cappozzo et al., 1976; Neumann, 2013).

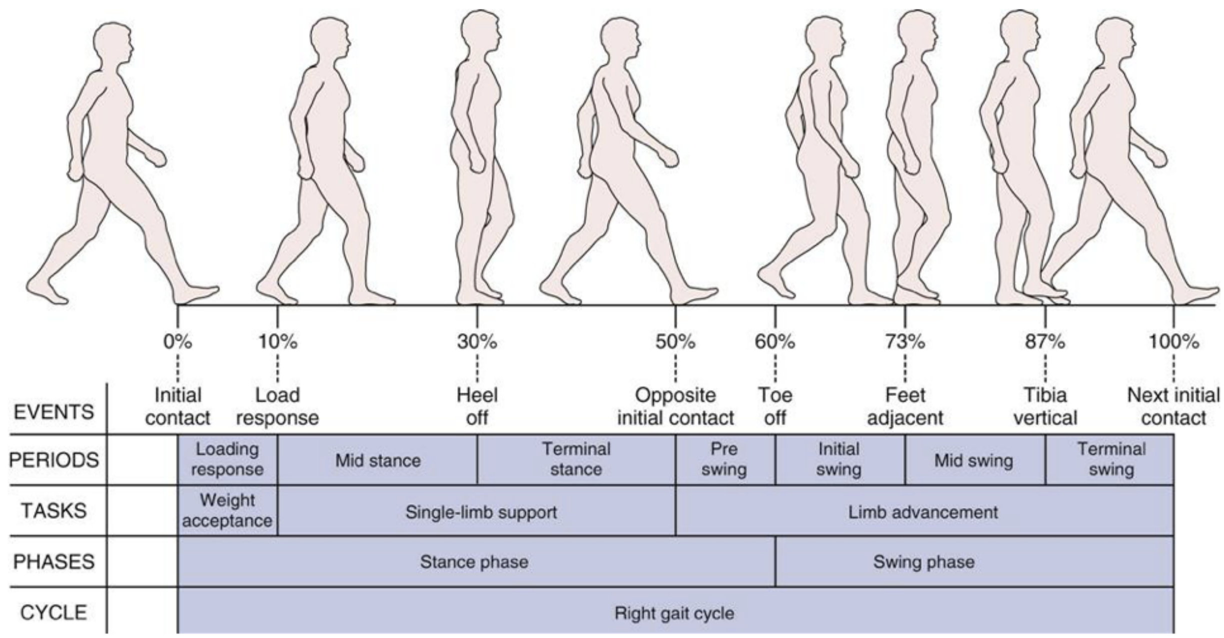


Figure 2.10. Gait cycles.
Note. Adapted from Assessment of Gait linked to https://clinicalgate.com/assessment-of-gait/

The human gait analysis is mainly divided into two key parts such as kinematics and kinetics, which are widely used among clinics and sports biomechanics to help patients and athletes in efficient diagnosis and rehabilitation from neuromuscular injuries (Davis et al., 1991). In general, walking situations, which significantly affect the magnitude of pressure on the hips, knees, and ankles, can face flat surfaces, ascending surfaces, descending surface and stairs differently than walking speeds during daily life (Lee & Park, 2011; Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007). Movements in biomechanics occur in all three planes (sagittal, frontal, and transverse planes). For example, hips lead to flexion-extension in the sagittal plane, adduction-abduction in the front plane, and internally-externally rotation in the transverse plane.

Kinematic Analysis of Locomotion

Kinematics refers to descriptions of human motion, including velocities, displacements, and accelerations of body joints and segments, without force (Whittle, 2014). Kinematic gait analysis is usually performed to capture the motion data using 3D motion capture equipment. Intersegmental joint angles (e.g., hip, knee, and ankle) and joint range of motion (ROM) of the lower limbs are the important variables in the spatial and temporal parameters during normal walking (Davis et al., 1991). If the degree of the flexion range is exceeded, the probability of the injuries could be increased (Oatis, 2009; Tao, Liu, Zheng, & Feng, 2012). Therefore, the parameters (e.g., degrees of the ROM and joint angle) offers detailed information associated with degrees of injury risk in the gait analysis using 3D motion capture systems (Kale et al., 2003; Oatis, 2009).

During walking, an upright or stable posture is particularly crucial, so it is necessary to wear appropriate shoes that can support lower limbs and encourage leg strength for walking stability (Nigg, Hintzen, & Ferber, 2006). To reduce potential risk factors during running and walking with comfort, a variety of shoes with technologies (e.g., gel, air, ethylene-vinyl acetate) in plantar areas (fore-, mid-, and hind-foot) have been developed (Dintato et al., 2015).

The functions of the midsole and outsole play a major role regarding the reduction of shock and impact of force during gait (Chiu & Wang, 2007). As arch shape of the insole can help longitudinal arches of the feet, the insole not only significantly influences foot problems (e.g., plantar facilities and abnormal arch diorthosis), but also reduces the plantar aponeurosis strain (Burgess, Jordan, & Bartlett, 1997; Kogler, Solomonidis, & Paul, 1996). Wearers are very sensitive to a material of soles that underlays the midfoot (Witana, Goonetilleke, Xiong, & Au, 2009). Midsole hardness significantly influences performance during running in the sagittal plane in a different age group (Nigg, Baltich, Maurer, & Federolf, 2012). There are small differences between smooth and textured insoles in the ankle angle during walking (Nurse, Hulliger, Wakeling, Nigg, & Stefanyshyn, 2005). However, Qu (2015) found that stiff insoles positively affect dynamic postural stability more than soft insoles, despite improving the performance of cupped insoles in the elderly.

Furthermore, when wearing shoes with a high degree of outsole, as compared to normal shoes on the current footwear market, gait significantly changes muscles and joints in the lower limbs (Landry, Nigg, & Tecante, 2010; Nigg et al, 2006). During gait, both the stability of the upright posture and the muscle movement of the lower limbs are impacted by the degree of the round angle of the outsole (Demura, Demura, Uchiyama, Kitabayashi, & Takahashi, 2015). Therefore, male wearers in the study were able to identify differences between in both a less cushion material (i.e., cork) of sustainable shoes and a cushioning material (i.e., polyurethane) of leather shoes in outsoles, due to use of different component, respectively.

Kinetic Analysis of Locomotion

Kinetics refers to a description of internal and external forces (ground reaction, body weight, momentum, and muscle), moment, mass, and acceleration acting on human body segments using a force platform embedded in the walking surface (Levine et al., 2012). The main measurement of kinetic analysis is ground reaction forces (GRF) regarding external forces acting on the human body segments, because of the application of inverse dynamics on the ground (Oatis, 2009). The GRF explained by a vertical direction is identical in terms of magnitude and in the opposite direction of the force (Oatis, 2009). Both stance phase of foot and the acceleration of the center of the mass are significantly associated with variation of the magnitude and direction of the GRF (Oatis, 2009). A regular pattern of GRF is a critical indicator in determining important factors during normal walking while an irregular pattern of GRF can provide useful information about efficient diagnosis, treatment, and rehabilitation for gait pathology.

Angle of walking and walking speeds are critical for examination in magnitudes of joint moments such as hips, knees, and ankles (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980). The results of the study showed that knee and hip flexion/extension moments are of higher value and the comparison of differences at the knee joint is the largest in contrast to ascending stairs and different walking speed conditions. Protopapadaki et al. (2007) found that ascending stairs requires more movement than descending stairs and walking speed conditions, because of the considerable variation in knee extension and hip moments. However, during stair descending, GRF showed the maximum values at the beginning of stance phases, while during ascending of stairs both hip extension and knee flexion moments hold maximum values (Protopapadaki et al., 2007). Controlling the pelvis in the frontal plane of the hip takes considerable effort during the ascending of stairs, due to concentric movements that raise the pelvis (Nadeau, McFadyen, & Malouin, 2003). During walking and running, the hip joint is impacted more than body weight by the force (Bergmann, Graichen, & Rohlmann, 1993). However, the most common shoe types (e.g., athletic shoe, leather shoes, hiking boots, and clogs) may not necessarily impact the body’s locomotion (Bergmann, Kniggendorf, Graichen, & Rohlmann, 1995). Hip joint loading was closely associated with stable walking in that the optimal footwear suggested for patients could enable stable walking (Bergmann et al., 1995). No differences for magnitudes of GRF between smooth and textured insoles during walking were found (Nurse et al., 2005). In sum, a variety of factors (e.g., material, length, width, shape, and weight) of the foot and footwear affect kinematic and kinetic analysis. The dynamic performance of foot should be considered by designers in footwear design. Human motion in hip, knee, and ankle allows accommodation to the environment and to gait alterations while speed, pattern, and weight are impacted by internal and external forces during walking. Therefore, the sustainable shoes made of eco-materials enable a similar effect of leather shoes on dynamic movement in kinetic and kinematic approach.

Consumers’ Perceptions of Sustainable Products

Consumers’ perceptions of sustainable products are limited by several boundaries in being an unfashionable or an unattractive product, lack of information, limited availability of products, and price (Gam, Cao, Farr, & Kang, 2010; Gleim, Smith, Andrews, & Cronin, 2013; Moon, Youn, Chang, & Yeung, 2013; Nam, Dong, & Lee, 2016). Moreover, to successfully launch new sustainable products into the market, companies or designers need to evaluate consumers’ acceptance (e.g., preference, wants, and needs) in product development stages (Lee et al., 2016). Cao et al. (2014a) pointed out that young consumers prefer purchasing a colorful scarf made from local natural materials and dyed with plants, because of the fashion and comfort of the items. Therefore, natural textiles and products can be marketed to attract consumers to purchase and to satisfy their aesthetic and functional needs.

Other obstacles that the consumers have experienced in seeking green sportswear were lack of information and limited availability of products (Nam et al., 2016). Cao et al., (2014b) found that a pair of shoes and a coat made from bio-based materials (i.e., plant oils, natural fiber cloth, and chicken feather fibers) and renewable materials (i.e., organic cotton and wool fabric) were comfortable through both wear tests and in data collected about subjects’ perceptions via the questionnaire. Important factors for young consumers to consider are the colorful and stylish design in sustainable shoes (Cao et al., 2014b). Consumers’ needs, perceptions, and expectations (fit, durability, and comfort) are positively affected by personal or indirect experience with new fabrics or products (Ismail & Spineli, 2012; Romeo & Niehm, 2015). Therefore, consumers can obtain information about sustainable products from a variety of experience. Based on the results of an analysis of users' acceptance of the apparel products by Lee et al. (2016), the BC material not only proved itself as a possibility in the making of shoes, grocery bags, hats, and curtains in the future. It is also a useful sustainable material for manufacture at low costs (Dayal & Catchmark, 2016).

Sustainable apparel purchases are mostly influenced by price rather than quality and style (Iwanow, McEachern, & Jeffrey, 2005). Price can significantly affect consumers' willingness to purchase sustainable products (Gam et al., 2010; Wier, Jensen, Andersen, & Millock, 2008). Consumers expected the price of sustainable apparel and footwear might be low or reasonable (Cao et al., 2014b; Gam et al., 2010), due to the premium price for sustainable products, in general. However, more than half of young consumers who participated were willing to pay more or a premium for sustainable apparel products (Hustvedt & Bemard, 2008; Lee et al., 2016).

The perceived comfort of shoes may be generated by multiple individual physical factors as material properties (Lee & Hong, 2005; Witana et al., 2009), skeletal alignment, (Miller, Nigg, Liu, Stefanyshyn, & Nurse, 2000), fit (Au & Goonetilleke, 2007; Witana, Feng, & Goonetilleke, 2004), and fashion (Au & Goonetilleke, 2007). Therefore, it is hard to define comfortable shoes and good fit in particular conditions. However, Witana et al. (2009) found that comfortable shoes require three traits such as a perceived feeling of protecting both the outer shell and midsole of shoes, as well as the stability of footwear.

In closing, the designers should consider wearer' acceptance in the last stage of implementation process of sustainable in order to manufacture footwear consumers want and need, due to differences of consumer's preference. Furthermore, to commercialize or enhance features of new footwear, designers or marketers need evaluation of the product (e.g., design, color, fit, function, comfort, and cost) by target consumers. Therefore, survey questionnaire on end-users' perceptions and acceptance of the sustainable shoes was conducted in this study.

Research Hypotheses

Based on the literature review, the following hypotheses (Hs) were proposed to test kinematics and kinetics of two types of shoes – sustainable shoe and commercial leather shoe prototypes via users' wear testing.

H1: There are no differences in stance time of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

H2: There are no differences in a peak angle in range of motions (i.e., hip, knee, and ankle) of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

H3: There are no significant differences in ground reaction forces (i.e., hip, knee, and ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

H4: There are no significant differences in joint moments (i.e., hip, knee, and ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

In addition, the survey questionnaire for wearer's perceptions and acceptance investigated comparison between commercial leather shoes and sustainable shoes in functional, expressive, and aesthetic needs, mobility, and wearer' acceptance (FEAMA) model. The following hypotheses were proposed:

H5: There are significant mean differences between commercial leather shoes and sustainable shoes in overall FEAMA model.

H6: There are significant mean differences between commercial leather shoes and sustainable shoes in functional consumer needs.

H7: There are significant mean differences between commercial leather shoes and sustainable shoes in expressive consumer needs.

H8: There are significant mean differences between commercial leather shoes and sustainable shoes in aesthetic consumer needs.

H9: There are significant mean differences between commercial leather shoes and sustainable shoes in mobility in three different conditions.

H10: There are significant mean differences between commercial leather shoes and sustainable shoes in wearer's acceptance.

Summary of Literature Review

The proposed footwear design model for this study was an adaptation of the cradle-to-cradle (C2C) model and the functional-expressive-aesthetic (FEA) consumer need model with sustainable apparel and product design processes. This design model also incorporated and selected principles (1, 2, 7, 10, and 11) of green engineering within the sustainable footwear development process. Therefore, the IsAcT design process for the sustainable footwear on three stages: Stage 1 – Problem identification and eco-material selection, Stage 2 – Eco-material assessment and prototype development, and Stage 3 – Wear testing of shoes and prototype evaluation in the proposed model may enable the explanation of a sustainable footwear. Therefore, the sustainable shoe prototype of this study mainly consisted of an outer shell (green tea based BC non-woven mat), a middle shell (denim fabric), an inner shell (hemp fabric), a midsole (compressed paper), and an outsole (cork material) using the C2C framework to minimize the use of chemical materials and encompassed five of 12 principles of green engineering.

The interaction of material's properties with wearers' senses can contributes to physical comfort and be related to physical stress during human performance, depending on the type of works and intensity, material composition, and thermal environment. The key features of the materials can be used to predict to wearable products' comfort without wearers' fatigue and discomfort in a clothing system.

The human gait analysis is mainly divided into two key parts, kinematic and kinetic approaches, which are widely used among clinics and sports biomechanics to help patients and athletes in efficient diagnosis and rehabilitation from neuromuscular injuries. Gait analysis was conducted to ensure a quantitative evaluation and interpret the kinematic and kinetic parameters on humans' lower extremity by identifying normal working patterns on different conditions for wear testing between leather shoes and sustainable shoes in the study. A majority of research regarding the consumers' perceptions and acceptance of sustainable products pointed out several issues such as fit, comfort, function, expression, aesthetics, and mobility. The questionnaire; therefore, was adapted and then administered to identify wearers' perceptions and acceptance of the sustainable shoes, which were then to be reflected in Stage 3, the wear testing of shoes prototype evaluation.

CHAPTER 3. METHODOLOGY

The overall purpose of this study was to identify the compatibility of sustainable shoes made with bacterial cellulosic (BC) non-woven mat, denim fabric and hemp fabric compared with durability and comfort in performance of newly developed sustainable shoes and commercially available leather shoes via users' wear testing, perceptions and acceptance within the proposed integrated sustainable footwear design framework.

This chapter includes: (a) proposal theoretical framework for sustainable shoes, (b) eco-material development, (c) preparation for material testing, (d) material testing, (e) wear testing, and (f) wearers' perceptions and acceptance. Different research methodological procedures are performed to examine the five study objectives using the following four studies (see Figure 3.1).

Study 1 (Objectives 1): Design and development of a proposal theoretical framework under cradle-to-cradle (C2C) model by integrating functional-expressive-aesthetic (FEA) consumers' need model with three stages of the IsAcT design process for sustainable footwear to: (a) Identify problems and select eco-material; (b) Assess eco-materials and create a prototype; and (c) Test human trial and wearer' acceptance. In this study, the 12 principles of green engineering were adapted and the following principles were incorporated within the shoe development process: Principles 1, 2, 7, 10, and 11.

Study 2 (Objective 2): Evaluation of selected multi-layered cellulosic material (MCM) by bonding BC non-woven mats, denim fabrics, and hemp fabrics compared with those of two-layered leathers, multi-layered calf-and pig-skin leathers (MCPL). The following was examined: physical, heat and moisture transfer, and mechanical properties.

Study 3 (Objective 3): Development of men's sustainable shoe prototypes made with BC non-woven mats, denim fabrics, hemp fabrics, compressed papers and cork materials.

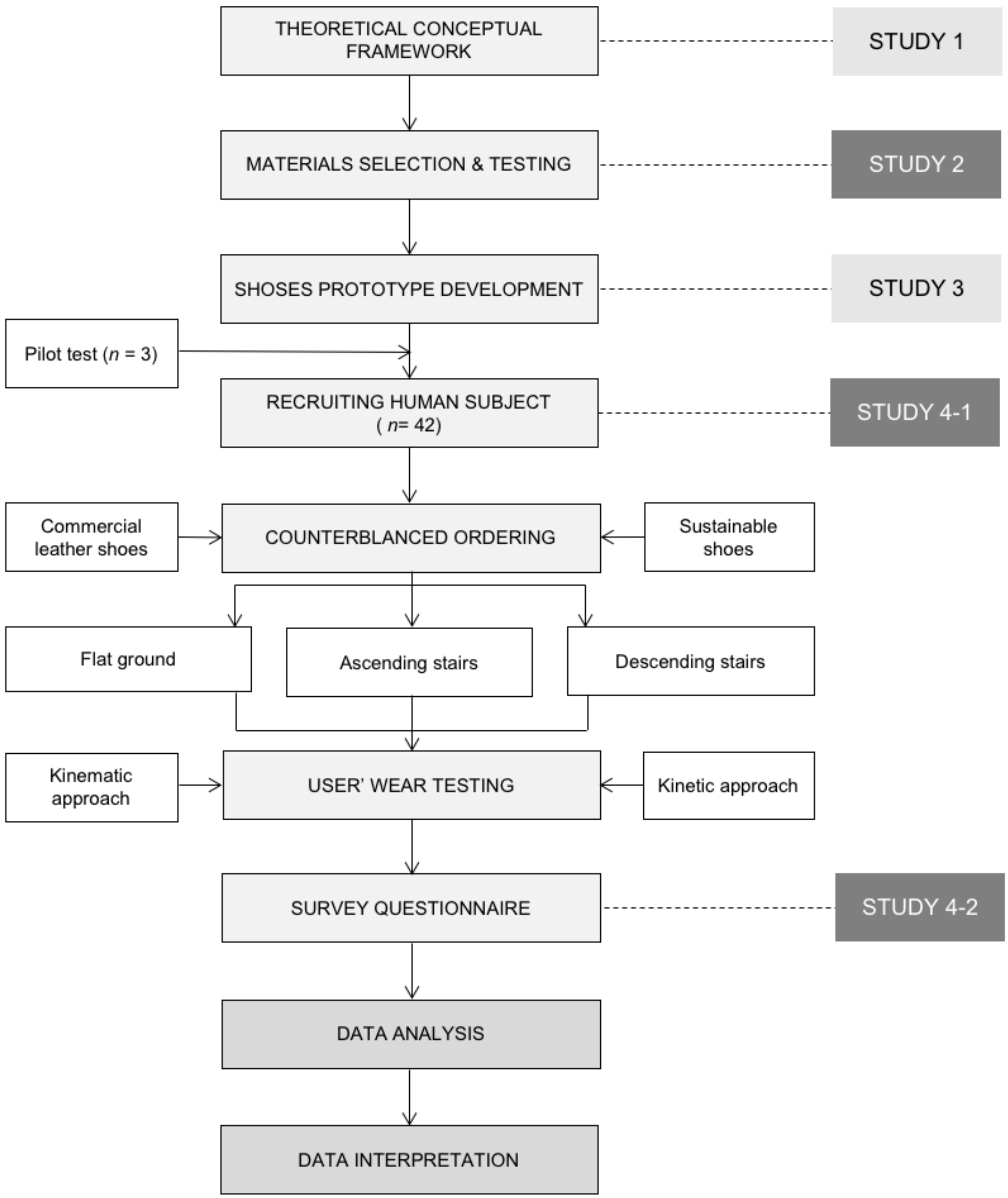


Figure 3.1. The overall research plan of this study.

Study 4 (Objective 4 and 5): Assessment of the performance of shoe prototype. In this study, the differences in lower body movement of wearers between sustainable shoes and commercial leather shoes are shown by using kinematic parameters (i.e., stance time, range of motion) and kinetic parameters (i.e., ground reaction force, joint moment) in three different walking conditions (i.e., flat ground, stair ascent, and stair descent). In addition, assessment of wearers' subjective perceptions and acceptance of the men's sustainable shoes via questionnaire. The questionnaire includes questions related to the functional-expressive-aesthetic needs, mobility, and wearers' perceptions of the sustainable dress shoes and leather shoes.

Proposal Theoretical Framework for Sustainable Shoes

Objective 1 of this study was to create a proposal theoretical framework under cradle-to-cradle (C2C; McDonough & Braungart, 2007) model, integrating with functional-expressive-aesthetic (FEA; Lamb & Kallal, 1992) consumer need model and sustainable apparel and product design processes (Cao et al., 2014b). Five (1, 2, 7, 10, and 11 principle) of the twelve principles of green engineering (Anastas & Zimmerman, 2003) were adapted and incorporated within the IsAcT design and process with three stages (problem identification & eco-material selection, prototype development & eco-material assessment, and wear testing and evaluation). Inspired by the concept of "sustainability" and based on previous shoe design made of a green tea-based biodegradable cellulosic fiber mat for outer shell, layered with synthetic leather for inner shell and polyurethane for outsole (Nam & Lee, 2016), the integrated theoretical framework was challenged to implement the sustainable shoe design process. Thus, designing and developing the men's sustainable dress shoes was focused on the sustainable material selection for each different layer of the shoe structure and simple pattern development using a zero waste design approach, which may lead to reduce negative environmental impact to achieve Objective 3.

Eco-Material Development

Objective 2 of this study was to evaluate materials selected the eco-layer materials (BC non-woven mat, denim fabric, and hemp fabric) used for sustainable shoes, comparing leathers (calf-and pig-skin leathers) for commercial leather shoes, based on literature reviews in Chapter 2. The materials test not only can determine suitability for use in that product, but also offer information that helps anticipate product performance such as in durability and comfort. Furthermore, aspects of durability are associated with end-of-life of a product, while aspects of comfort affect performance and the aesthetics of the material (Kadolph, 2010).

Three main material properties (basic, heat and moisture transfer, and mechanical) are related to a wearer's thermal comfort during walking. First, basic properties of weight, thickness, and air permeability of material generally promote physical stress on the wearer. Second, heat and moisture transfer properties have an important effect on the comfort of a wearable product (McQuerry et al., 2017; Wen, 2014). Third, tensile strength, wettability, and tactile comfort are not only associated with the mechanical interaction between the footwear materials and the human body, but also impacts intrinsic and specific performance of the wearable products (Raj & Sreenivasan, 2009). Therefore, for designing and developing sustainable shoes, in this study, we aimed to develop a multi-layered cellulosic material (MCM) and examine its properties (i.e., thickness, weight, air permeability, thermal comfort, tensile strength, and wettability) compared with those of commercially available a two-layered leather (MCPL) often used when making shoes (see Figure 3.2).

Material Selection

This study focused on evaluation of a multi-layered cellulosic material (BC non-woven mat, denim fabric, and hemp fabric) for the use in sustainable footwear, wear testing, and consumer acceptance of sustainable footwear funded by the EPA P3 Phase II "Developing

Sustainable Products Using Renewable Cellulose Fiber and Biopolymer Composites" (The United States EPA Grant No. SU835733). Based on the previous research reported BC mats (Lee et al., 2014), the process of this study required the optimal combination of ingredients (i.e., 3760ml water, 9 organic green tea bags, 540g cane sugar, 632ml vinegar and then added approximately 100g commercial organic SCOBY) in a 11.5" × 16.75" plastic container at 80-85°F with relative humidity of 16-26%. In this study, the BC mats were harvested after four weeks of growth. After harvesting, the mats were washed and boiled in deionized water as a purification process by washing (three times) and one time boiling session (30 minutes), to remove sugar and other impurities, and then they were completely air-dried in the same room for one week.

Single-layered materials for sustainable shoes prototypes. The three main materials used in this study were the green tea-based BC non-woven mats, denim fabrics (twill weave, 100% cotton), and 100% hemp fabrics (plain weave). The BC non-woven mats were completely produced for six weeks. The denim and hemp fabrics were purchased from a textile market.

Single-layered materials for commercial shoes prototypes. The two main materials, which are most common leathers (calf- and pig-skin leathers) commercially available and often used when making shoes, were purchased from a leather shoe factory in Seoul, South Korea.

Multi-layered materials. Both three materials (i.e., BC non-woven mat, denim fabric, and hemp fabric) for a multi-layered cellulosic material (MCM) and two materials (i.e., calf- and pig-skin leathers) for a two-layered leather (MCPL) were proposed.

In sum, a total of seven different layer configurations were prepared for the experiments: five single-layered materials (i.e., BC non-woven mat, denim fabric, hemp fabric, calf-skin leather, and pig-skin leather) and two multi-layered materials (i.e., MCM and MCPL).

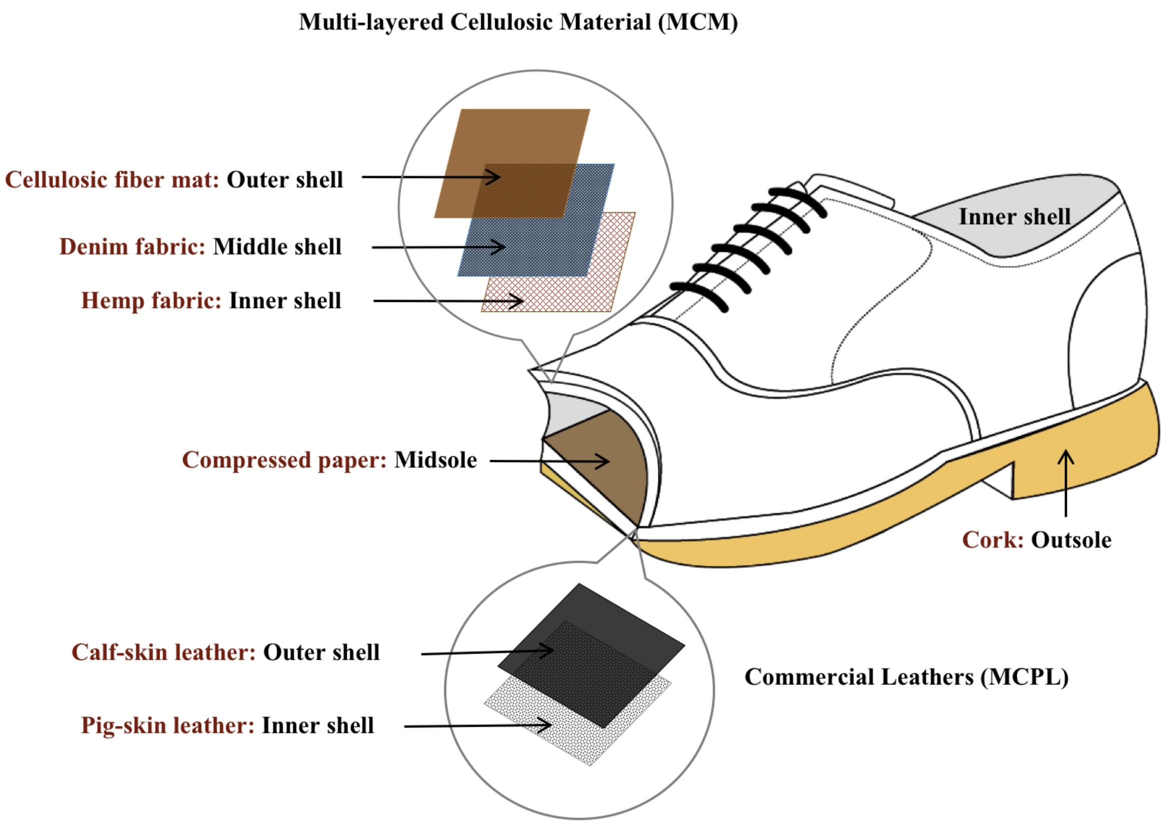


Figure 3.2. Material structures in footwear created by the researcher.

Preparation for Material Testing

The material properties examined in this study were: (a) physical properties, (b) heat and moisture transfer properties, and (c) mechanical properties. Properties of single-layered materials were examined first, followed by an analysis of two separately combined materials – MCM and MCPL. Depending on the types of testing, all materials were cut into four different sample sizes: (a) 50cm x 50cm for a sweating guarded hotplate, (b) 25cm x 25cm for an air permeability apparatus, (c) 10cm x 15cm for a tensile testing machine, (d) 2.5cm x 10cm for an Instron, and (e) 2.5cm x 5cm for an optical contact angle instrument. For each material testing property, all material samples (BC non-woven mat, denim fabric, hemp fabric, calf-skin leather, pig-skin leather, MCM and MCPL) were examined three times using suitable instruments by following the standard testing method ASTMs.

Instrument for Material Property Testing

Digital electronic caliper and scale. Both inside and outside areas of materials using upper and lower jaws were measured thickness (mm) of each material with a Mitutoyo absolute digimatic caliper 500 (Mitutoyo, Illinois, Chicago). The weight (g/cm^2) of each material was measured using a Mettler Toledo scale (GmbH, Switzerland).

Sweating guarded hotplate instrument. The heat and moisture transfer from the human body surface through fabrics to the environment (Huang, 2006), designed for the measurement of thermal resistance (R_{ct}) and water vapor resistance (R_{et}) of fabrics, to help determine the comfort of the wearer, were measured with a sweating guarded hotplate instrument (Measurement Technology Northwest SGHP-10.5, Seattle, Washington) by following the standard testing method ASTM F1868 (American Society for Testing and Materials, 2014).

Air permeability apparatus. Air permeability (cfm) were measured in test area (38cm^2) and test pressure (125Pa) of each material on an air permeability tester (SDL Atlas®, China) based on ASTEM D737 (2008).

Tensile tester. Tensile testing was conducted with two types of tensile testers (Tinius Olsen testing machine and Instron instrument) with ASTM standard methods, respectively. The following is the details of each machine:

(1) Tinius Olsen testing machine – The instrument determines mechanical properties such as breaking strength and elongation of each sample by averaging values mean (N) and standard deviation (SD) measured using a tensile machine (Tinius Olsen®, UK) with a load cell (1N) and a test speed (300mm/min) according to the ASTM D5034 (2011). The machine with the 5000N loading cell was set to the recommended loading rate (300 ± 10mm/min).

(2) Instron equipment – A tensile testing system machine (Instron ® 5900 Series Model 5966, Norwood, Massachusetts) offers exceptional performance testing and is designed with enhancements that deliver unparalleled accuracy and reliability, improved ergonomics, and an enhanced overall experience for the operator followed by the ASTM D882 (2014). The most common uses of the mechanical testing systems are for tensile, compression, bend, peel, shear, and tear tests.

Optical contact angle instrument. The contact angle measurement and drop shape analysis with a high performance zoom lens and video measuring system were measured using an optical contact angle and contour analysis 25 instrument (DataPhysics Instruments GmbH, Filderstadt, Germany) for testing fabric's wettability. The spreading process and angle of water droplets on the materials' surfaces was recorded.

Material Testing

Material testing was carried out with a total of seven types of samples: BC non-woven mat, denim (twill weave) fabric, hemp (plain weave) fabric, calf-skin leather, pig-skin leather, MCM, and MCPL. All materials were conditioned at 21ºC ± 1ºC and 64% ± 2% relative humidity for three days before the testing. All samples were investigated three times using appropriate instrument for physical, heat and moisture transfer, and mechanical properties.

Physical Properties

Thickness (mm) and weight (g/cm^2) were tested using a digital electronic caliper (Mitutoyo, Illinois, Chicago) and a Mettler Toledo scale (Mettler Toledo GmbH, Switzerland), respectively. The air permeability (AP; cfm) of the samples was measured with an air permeability tester (SDL Atlas®, China) based on the ASTM D-737 standard method (2008), with the test area of 38cm^2 at a test pressure of 125Pa.

Heat and Moisture Transfer Properties

Thermal resistance and water vapor resistance. For wearers' shoe comfort of wearer, thermal resistance (R_{ct}) and water vapor resistance (R_{et}) of BC non-woven mat, denim fabric, hemp fabric, calf-skin, and pig-skin leather, MCM, and MCPL, were measured using a sweating guarded hotplate instrument in both ambient temperature of 20°C and 65% relative humidity in Part A (R_{ct}) and ambient temperature of 35°C and 40% relative humidity in Part B (R_{et}), according to the Part A and B of ASTM F-1868 (2014). Thus, thermal resistance (Part A) of five single-layered materials, and two multi-layered materials (MCM and MCPL) was first conducted and then water vapor resistance (Part B) of them was tested.

Total heat loss and permeability index. Thermal resistance (R_{ct}) and water vapor resistance (R_{et}) were evaluated with the sweating guarded hotplate. Total heat loss (THL) was calculated according to the following equation by McQuerry et al. (2017):

$$\mathrm{THL}\ (_{\text{predicted, TRH}}) = \frac{T_s - T_a}{R_{ct}} + \frac{P_s - P_a}{R_{et}}$$

T_s is the specified temperature at hotplate surface, T_a is the specified temperature of location environment, P_s is the calculated water vapor pressure at the surface of the hotplate, and P_a is the calculated water vapor pressure at the surface of the hotplate. R_{ct} (°C·W/m^2) is total thermal resistance of the test ensemble and surface air layer and R_{et} (Pa·W/m^2) is total evaporative resistance of the test ensemble and surface air layer. The permeability index (i_m) was calculated according to the following equation by Woodcock (1962):

$$\text{Permeability index } (i_m) = \frac{R_{ct}}{LR \times R_{et}}$$

Lewis relation (LR) is the ratio of evaporative mass transfer coefficient to convective heat transfer coefficient. The value varies slightly with air temperature, pressure, and humidity. For most typical applications it can be treated as a constant equivalent to 16.65°C/kPa

(McCullough, 1993). For THL and permeability index, both values of R_{ct} and R_{et} were adapted from thermal and water vapor resistance obtained from the hotplate testing.

Evaporative potential. Evaporative potential (EP) was calculated along with the R_{cf} (°C·W/m^2)/0.155 formula of thermal insulation (clo) and the permeability index (i_m) of materials, based on the following equation by Martin and Glodman (1972). EP can indicate whether or not the wearer potentially has heat stress associated with wear's comfort (Chang & Gonzalez, 1999).

$$\text{Evaporative potential (EP)} = \frac{i_m}{\text{clo}}$$

Mechanical Properties

In this study, tensile strength was evaluated using two different equipment and standard methods (ASTM D-5034 and ASTM D-882) to deeply understand the mechanical properties. Figure 3.3 exhibits the mechanical properties of material behavior under stress and strain according to the Interconnecting and packaging electronic circuits (Association Connecting Electronics Industries, 1995) test method manual (p. 2-3): "(a) tensile strength is calculated by dividing the load break by the original minimum cross-section area, (b) elongation is calculated by dividing the elongation at the moment of rupture by the initial gauge length and multiplying by 100, and (c) Young's modulus is calculated by drawing a tangent to the initial linear portion of the stress-strain curve, selecting any point on this tangent, and dividing the tensile stress by the corresponding strain."

Tensile strength (ASTM D-5034 method). Thickness (mm), width (mm), and length (mm) of each specimen was measured. The break force (N) and elongation (%) of five single-layered materials and two multi-layered materials (MCM and MCPL) were determined by averaging the measured values using a tensile testing equipment (Tinius Olsen®, UK) guided by the ASTM D-5034 standard test method for breaking strength and elongation of textile fabrics.

Tensile strength (ASTM D-882 method). To further analyze the tensile strength, Instron instrument was implemented to determine tensile strength (MPa), elongation at break (%), Young's modulus (MPa), and load at break (N) of single- and multi-layered materials, according to the ASTM D-882 standard method for tensile properties of thin plastic sheeting. The tensile testing system with the Instron software (Bluehill 3) was carried out tensile strength tests comparing five single-layered and two multi-layered materials.

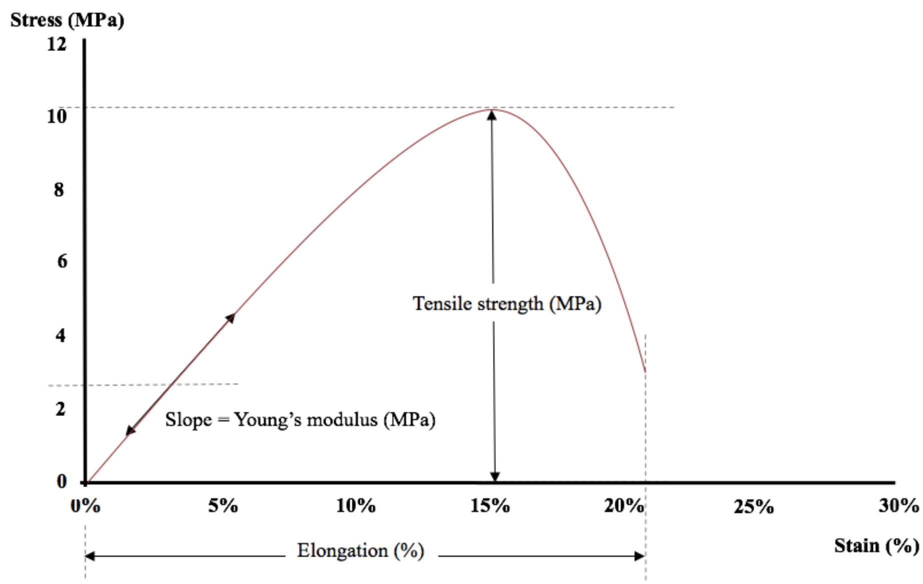


Figure 3.3. Material behavior under stress and strain created by the researcher.

Wettability. Contact angle (CA, º) for wettability was measured with a deionized water droplet of 2.00µL on each sample surface using a DataPhysics system, optical determination of the contact angle machine 20 (OCA). A contact angle of water drop shape on each material surface was measured using a contact angle and contour analysis 25 based on the Sessile drop-method with SCA software. Through the spreading and permeating behavior of water on the surface of each of the materials depending on degree of wetting angles (Sabreen, 2012) (see Figure 3.4), right contact angle of all materials was evaluated three times in this study.

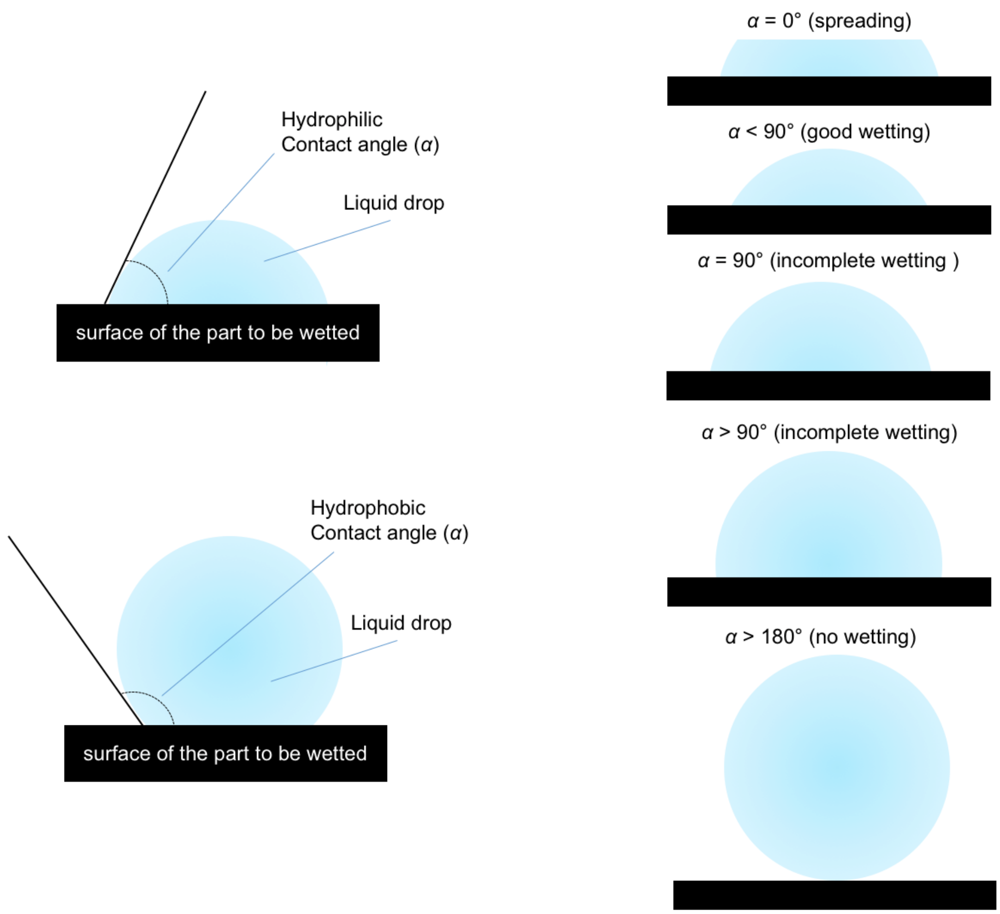


Figure 3.4. Theory of contact angles created by the researcher.

Data Analysis Procedures for Material Testing

The mean (M) and standard deviation (SD) values of a total of seven samples (i.e., BC non-woven mat, denim fabric, and hemp fabric, MCM, and MCPL) were first calculated. Using SPSS software 21, post-hoc comparisons with Turkey HSD test and an independent sample *t*-test were performed to identify mean differences of properties (i.e., thickness, air permeability, weight, thermal resistance, water vapor resistance, total heat loss, permeability index, break force, elongation, tensile strength, elongation at break, load at break, Young' modulus, contact angle) at *p*-value of 0.05. The results of materials tests are discussed in Chapter 4.

Sustainable Shoe Design and Development

The IsAcT design process and development for the sustainable footwear in the study were performed based on a proposal theoretical framework integrating cradle-to-cradle (C2C; McDonough & Braungart, 2007) model, sustainable apparel and product design processes (Cao et al., 2014b), functional-expressive-aesthetic (FEA; Lamb & Kallal, 1992) consumer need model. 12 principles of green engineering (Anastas & Zimmerman, 2003) were adapted and their five principles (1, 2, 7, 10, and 11). Inspired by the concept of "sustainability" and based on previous shoe design made of a green tea-based biodegradable cellulosic fiber mat for outer shell, layered with synthetic leather for inner shell and polyurethane for outsole (Nam & Lee, 2016), the integrated theoretical framework was challenged to implement the sustainable shoe design process. Designing the men's sustainable shoes was focused on the sustainable material selection of the shoe structure and simple pattern development using a zero waste design approach, which may lead to reduce negative environmental impact to achieve Objective 3.

Multiple Steps of the Shoes Design and Development

The sustainable design and development involved three steps: (a) design ideation including sketching for shoe prototypes and pattern-making using a shoe last, (b) sustainable material selection (MCM, compressed papers, and cork materials) for upper shell, midsole, and outsole respectively, and (c) assembling the upper shell and outsole.

Design Ideation for Sustainable Shoes (Stage1)

The sustainable shoe design considered much attention to wearers' functional and aesthetic desires since these shoes are made with eco-friendly materials and are a human's prime point of contact with nature. A multi-layered cellulosic material (MCM- BC non-woven mats, denim fabrics, and hemp fabrics) of sustainable shoes were inspired by an outdoor clothing layering system (see Figure 3.5).

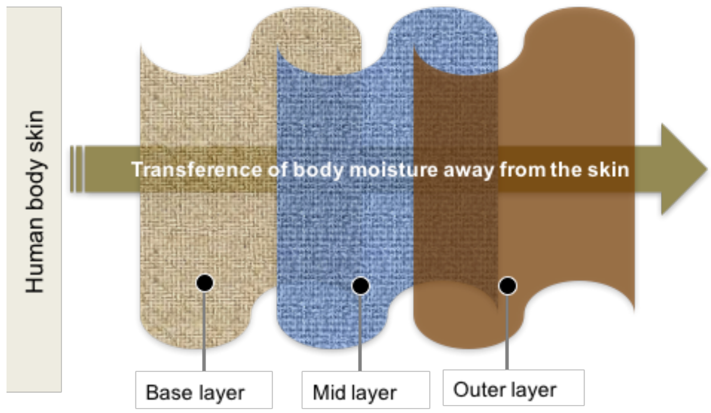


Figure 3.5. An outdoor clothing layering system created by the researcher.

In the preliminary idea generation (Stage 1), various supplementary materials were used to visually facilitate the brainstorming process. Then, emergent ideas and concepts were organized and roughly sketched by hand using a piece of paper and pencil. To reach the design refinement stage, style ideas was developed, refined, and visualized on the style in the paper then with computer software (Adobe Illustrator; see Figure 3.6). A contemporary look for the sustainable shoe design, inspired by the “loafer style,” lace-less shoes, can complement current college male students’ desires and needs of shoes in their urban campus life. The design and pattern were executed by hand using a plastic shoes last (see Figure 3.7). The sketching and ideation stage for sustianable shoes then led to the pattern-making.

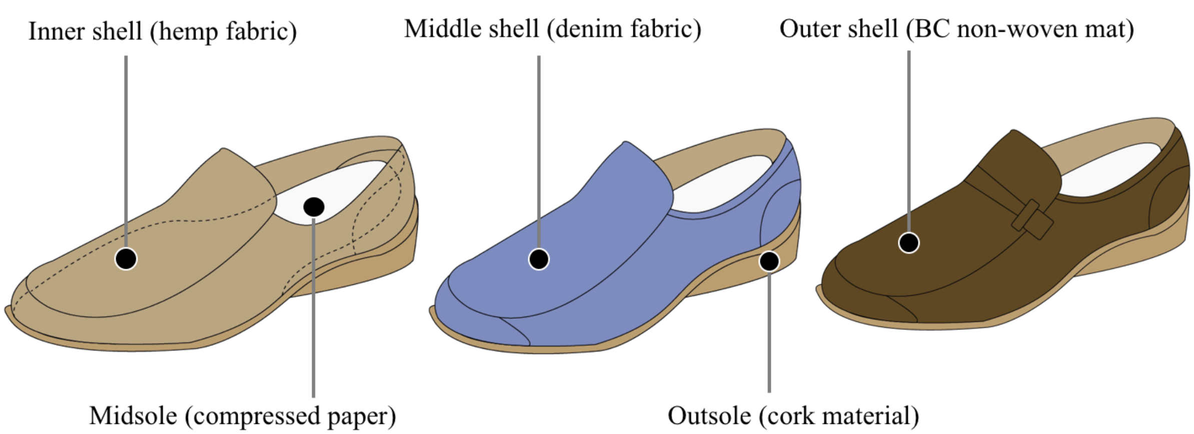


Figure 3.6. Sketching for design ideation created by the researcher.

Figure 3.7. Sketching and pattern-making created by the researcher.

Once design sketches were finalized, simple shoe patterns were developed and refined by reusing packaging papers and worn out jeans. As shown in Figure 3.7, initial pattern-makings using worn (seven-year-old) jeans were considered a zero waste approach (Stage 1). The sustainable shoes were considered as durable (Principle 7) and as optimized products in designed with closed-loop material flows (Principle 10), based on the commercial after-life processes (Principle 11) in sustainable product design.

Sustainable Material Selection (Stage 1)

For the material selection (part of Stage1), green tea-based BC non-woven mats, the main shell material of the shoes, was grown and proceeded to fully implement sustainability design practices for reducing negative environmental impacts that might be caused by prototype development processes. In this study, eco-materials (Principle 1) were selected from environmental friendly and safe materials (i.e., BC non-woven mat, denim fabric, hemp fabric, compressed paper, and cork material) without dangerous waste (Principle 2), and with durability (Principle 7). Therefore, the end-of-life for the shoes could be considered as designing with closed-loop material flows (Principle 10). During the prototype development (Stage 2), the production processes were carefully examined and chosen, after reviewing the sustainability matrix and determining the feasibility of meeting the target quality for each shoe. Considering the C2C design system, the sustainable shoes was created using eco-friendly materials.

Moreover, to enhance aesthetic appealing of the sustainable shoes and purchase intention for attracting eco-conscious young male consumers to wear the shoes in their urban campus life, the BC non-woven mats (outer shells) were naturally dyed with leftover coffee grounds in order to replicate the color of Van Dyke brown (Nam & Lee 2016; Nam & Xiang, 2014).

Assembling Upper Shell and Outsole (Stage 2)

As shown in Figure 3.8, the men' dress shoes consisted of MCM (BC non-woven mat, denim fabric, and hemp fabric) to improve the strength and performance and give the same function as commercial leather shoes, based on the three layered clothing system.

(a) Inner shell- hemp fabric layer (b) Middle shell- denim fabric layer (a) Outer shell- BC non-woven mat layer

Figure 3.8. Three shell structures of the shoe prototype developed by the researcher.

As shown in Figure 3.9, in this study, the sustainable shoes were unnecessary to insert a shank in midsole, which prevent the sole from collapsing on itself (Principle 2), because the flat outsole made of cork does not significantly influence on structure of these sustainable shoes between midsole (compressed paper) and outsole (cork material).

Figure 3.9. Components of the prototype shoes developed by researcher.

As shown in Figure 3.10, the MCM shell was covered with a last using assembling machine. Then the outsoles made of cork materials were measured and grinded depending on each shoes sizes. Finally, the main components (entire shell and outsole) of sustainable shoe prototype were attached using glue by a variety of machines in a shoe factory.

Figure 3.10. Assembling processes and designing outsole form of the shoe prototype.

As shown in Figure 3.11, in this study, the prototype shoes for wear testing were developed by the researcher, with three different sizes of men's shoes such as US size(mm) 9.5(270), 10(275), and 10.5(280) respectively because males, on the global average from the Statistic Brain Research Institute (2015), wear sizes ranging from 9 to 12 (two extra 10 and 10 .5 US sizes). Three pairs of commercial leather shoes (with three different sizes – 9.5, 10, and 10.5 US) were manufactured by professional shoe makers in a footwear manufacturing company supported this research. Therefore, to avoid bias in the manufacturing process, both the prototypes of sustainable shoes and the commercial leather shoes were made with the same shoe making equipment in the shoe factory.

(a) 9.5 (270mm) US size (b) 10 (275mm) US size (c) 10.5 (280mm) US size

*Figure 3.11.*Three different sizes of shoe prototypes created by the researcher.

Consequently, design patterns of men's sustainable shoes were created and procedures for making the shoes follow those steps commonly used for making commercial shoes, including the same, step-by-step manufacturing processes: (a) design and pattern, (b) materials preparation, (c) stitching operation, (d) outsole forming, (e) assembly, and (f) finishing coat using shoe-marking equipment. The different views of prototype sustainable shoes are presented in Appendix L.

A summary of the primary structures and materials for both sustainable shoe and leather shoe prototypes is presented in Table 3.1.

Table 3.1. *Structures for Sustainable and Leather Shoe Prototypes*

Part of shoes	Features /Roles	Material Structures	
		Leather Shoes	Sustainable Shoes
Outer shell (toe box, vamp, tongue, quarter, backstay)	hold the shoe on the foot	calf-skin leather: non-woven fabric	bacterial cellulosic (BC) non-woven fabric
Middle shell	support upper shell	n/a	denim, 100 % cotton: twill weave fabric
Inner shell (lining)	soft to the touch fabric on skin of foot	pig-skin leahter: non-woven fabric	100% hemp: plain weave fabric
Midsole	layer in between outsole and insole	compressed paper, synthetic resin	compressed paper
Shank	support stucture beween the midsole and outsole	rigid material (iron or metal)	n/a
Outsole	layer in contact with the ground	polyurethane	compressed cork

The sustainable shoes were structured with three main parts: shell, midsole, and outsole. In terms of material selection, three different eco-friendly layer configurations were featured of the entire shell: BC non-woven mats for outer shell, denim fabric for middle shell, and hemp fabric for inner shell. The outsole was made of natural cork, designed to fit the upper shell, and to provide comfort of the wearer. The flat shape was chosen for the outsole, which can appropriately support human feet and body without high pressure rather than the heel shape of outsole for men dress shoes. However, the commercial leather shoes were designed to a slightly round shape of outsoles by professional shoe makers in the study. Therefore, outsole shapes and materials of the shoes had the main difference between sustainable shoes and leather shoes using the same patterns provided by a researcher.

Wear Testing of Leather Shoes and Sustainable Shoes

Objective 4 of this study was to objectively evaluate the performance of the shoes on subjects by using quantitative kinematic and kinetic parameters of their lower body movements, which demonstrated the compatibility of MCM-based sustainable shoes to leather-based commercial shoes. In this Stage 3, the differences in lower body movement of wearers between sustainable shoes and commercial leather shoes were analyzed, using motion captures and force platforms by comparing kinematic parameters (i.e., stance time and range of motion) and kinetic parameters (i.e., ground reaction force and joint moments) in three different walking motions (i.e., walking on flat ground, ascending stairs, and descending stairs). As shown in Figure 3.13, a total of 21 retroreflective markers were placed on each joint of the lower limbs of male participants using 3D motion capture system (Vicon MX, Vicon, Centennial, CO) with eight cameras and four force platforms (Advanced Mechanical Technology Inc., Watertown, MA) available in the Biomechanics Laboratory in the Department of Kinesiology at Iowa State University.

The test results were used for answering the following four hypotheses:

H1: There are no differences in stance time of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) flat ground, (b) ascending stairs, and (c) descending stairs.

H2: There are no differences in peak angle in range of motions (e.g., hip, knee, ankle) of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) flat ground, (b) ascending stairs, and (c) descending stairs.

H3: There are no significant differences in ground reaction forces (e.g., hip, knee, ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) flat ground, (b) ascending stairs, and (c) descending stairs.

H4: There are no significant differences in joint moments (e.g., hip, knee, ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) flat ground, (b) ascending stairs, and (c) descending stairs.

Independent variables. Independent variables consisted of two different types of shoes: (a) sustainable shoes and (b) commercial leather shoes, and were assigned within subjects. Each subject was assigned to three different walking conditions (e.g., flat ground, ascending stairs, and descending stairs) according to a counterbalanced ordering (see Appendix I).

Dependent variables. Dependent variables include measurements of two different apparatuses: (a) stance time, (b) peak angle in range of motions (ROM) for kinematic variables using 3D motion capture system, (c) ground reaction force (GRF), and (d) joint moment for kinetic variables using a force platform.

All stride events were expressed as percentage of stride cycle during walking. Stance time is defined as a dominant foot contact on a force plate and move to next step. A peak angle in ROM at each joint (e.g., hip, knee, and ankle) in the lower limbs refers to the total amount of angular displacement and direction through movement between two adjacent segments using a motion capture (Kreighbaum & Barthels, 1996). The ground reaction force (GRF), as a distinct external force, was measured using a force platform during walking (Robertson et al., 2004). The six signals of the GRF were collected from the force platform. The form of six signals that consists of three orthogonal forces (F_x, F_y, F_z) and three moments (M_x, M_y, M_z) is in voltage (Robertson et al., 2004). An inverse dynamic method, a common method to calculate joint moments (e.g., hip, knee, and ankle), is validated by the moments' correspondence with normal muscle activity during walking. The kinetic data can be temporally and spatially integrated with kinematic data (Robertson et al., 2004). The reason is that muscles produce moments of forces across joints during the walking cycle (Kreighbaum & Barthels, 1996). The support moment is the sum of the extensor moments. The joint moments were measured in the sagittal, frontal, and transverse planes during normal walking.

Statement on the Use of Human Subjects

Institutional Review Board (IRB) approval (see Appendix A) was obtained from the University's Human Subjective Review Committee On June 07, 2017 before conducting the wear testing of this study. The IRB agreed that the rights and welfare of human subjects were protected, that the confidentiality of the data from voluntary participants were assured, that any possible risks to the subjects were avoided, and that the data of this study were obtained by appropriate procedures of informed consent (see Appendix B).

Population and Sampling Procedures

Participants were recruited from Iowa State University students through the University e-mails (see Appendix C), class announcements (see Appendix D), flyers (see Appendix E), and word of mouth. Some students in selected courses were received the announcement about the study by email. The flyers were posted in Forker, LeBaron, and MacKay buildings. Verbal announcement was made in classes. An e-mail advertisement explaining the study and inviting participants were sent out to a selected number of ISU students via listserve. Persons willing to participate were asked to contact the study investigators.

To clearly investigate the significant effect of the independent variables on the dependent variables, the following physical attributes of participants: healthiness of the men, shoe size, foot size, height, and weight were asked or measured in this study. Healthy male participants were volunteers who were interested in testing new sustainable shoes and who have not been injured or operated on in the lower body.

Statistical power analysis. Before starting data collection, this study conducted two types of power analysis such as A priori and post hoc power with an estimated effect size using G-power software. For a priori power analysis, the necessary sample size (n) is computed as function of desired specified values for the required significance level (α), statistical power (1- β)

a set at over 0.80 and to be identified population effect size (*d*) prior to a main study in order to reduce type II error (Bredenkamp, 1969; Brown, Palmieri-Smith, & McLean, 2009; Cohen, 1988). The priori statistical power using a matched pair *t*-test indicated the effect size (*d*) with Cronbach α = 0.05 and power over 0.8 was considered as 0.2 (small), 0.5 (medium), and 0.8 (large) using Cohen's (1988) criteria. As shown in Table 3.2, 80% statistical power with each effect size of Cohen's *d* indicated sample size estimates (*n* = 199, 34, and 15), respectively.

Table 3.2. *Results of A Priori Power Analysis*

	Difference between two dependent means (matched pairs)	
Effect size (*d*)	Actual power	Sample size
0.2 (small)	0.80	199
0.5 (medium)	0.81	34
0.8 (large)	0.82	15

Note. gray shading for target power and sample sizes.

Approximately 80% power with effect size of *d* = 0.3 (α < 0.05) presented estimates of the necessary sample size (approximately 34 subjects or over) required based on statistical power criteria (see Figure 3.12). Therefore, a total of 42 male participants were recruited in this study.

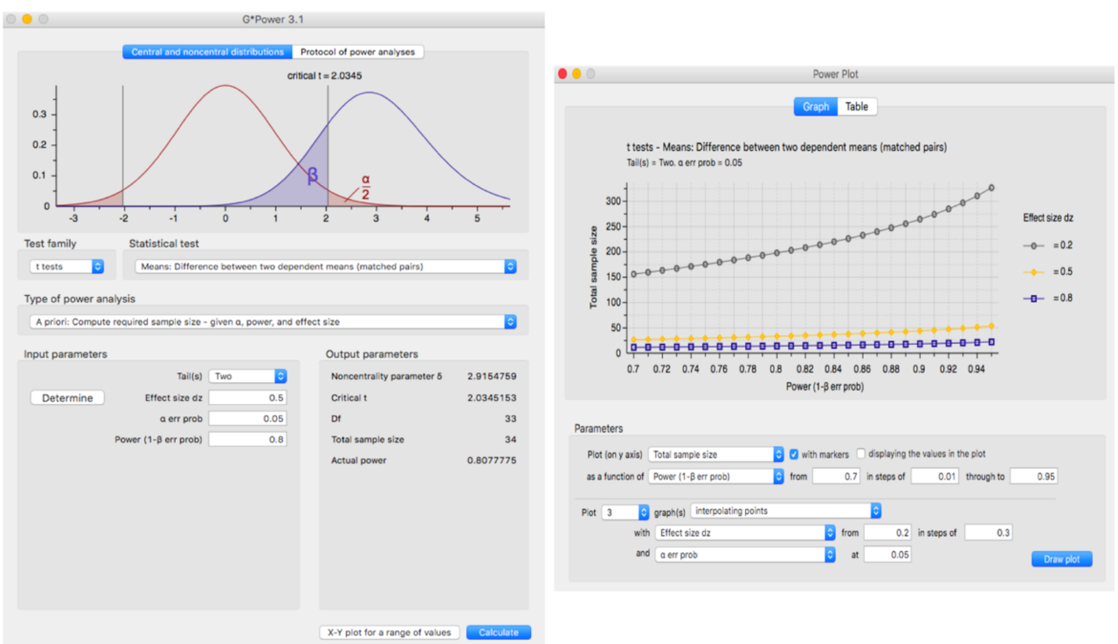


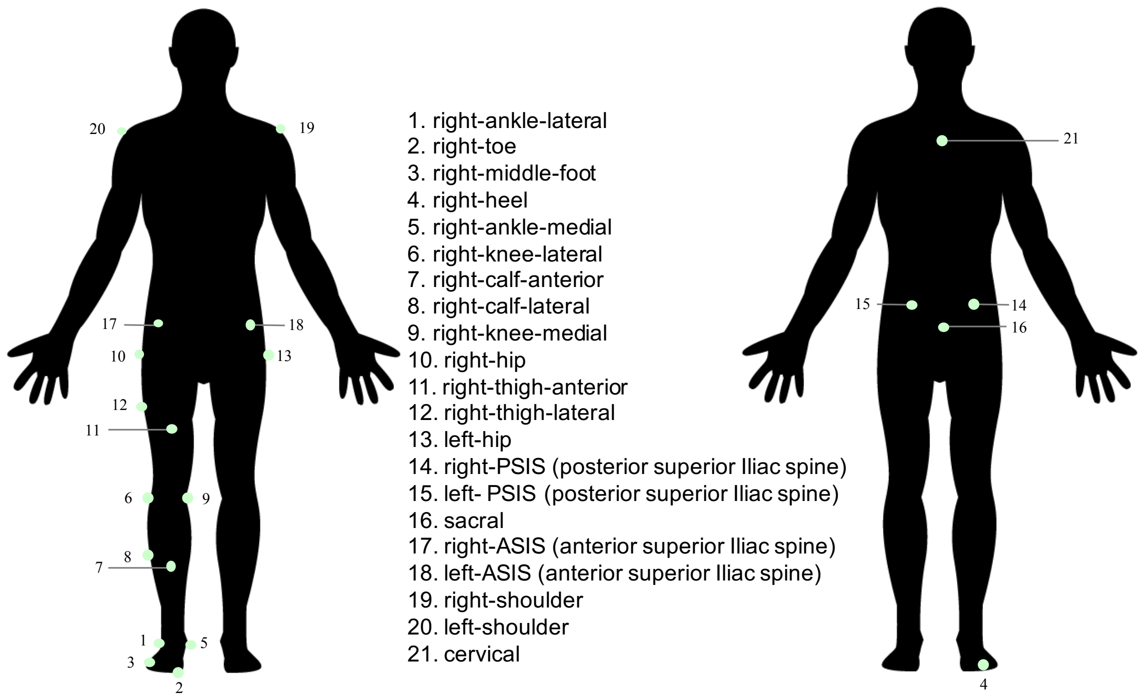
Figure 3.12. Priori power analysis of the paired simple t-test using G-power software.

Data Collection Procedures

Pilot study. A pilot study was conducted to test the experimental research design and the survey instrument with a pilot study evaluation form (see Appendix G), prior to the actual study in order to assess the validity and reliability of the proposed research (Creswell, 2003). Three male subjects who participated in the pilot test were examined as 10% of the main study sample size (Hertzog, 2008) at a biomechanics laboratory; however, the subjects of the pilot study were not be included in the actual, main study. An informed consent form was signed by each participant before the pilot study.

Main study. A convenience and purposive sampling approach involving 42 male human subject aged 18 years and over who wear the United States shoes sizes ranging from 9.5 to 10.5 was used. All recruited male volunteers agreed to participate in the study by signing an informed consent (see Appendix B) form before their participation. According to the counterbalanced ordering (see Appendix I), each human subject wore either men's commercial leather shoes or sustainable shoes prototype, which was part of a blind test that is used to make the human subjects blind to which shoes they were being given. The participants were asked to engage in three different walking movements for the kinematic and kinetic test for three separate trials. After finishing the experimental tests, each participant was asked to fill out the questionnaire regarding demographics, measurement, as well as wearer' perceptions and acceptance (see Appendix J and Appendix K, respectively). All participants received a $10 Starbucks gift card as compensation for this study.

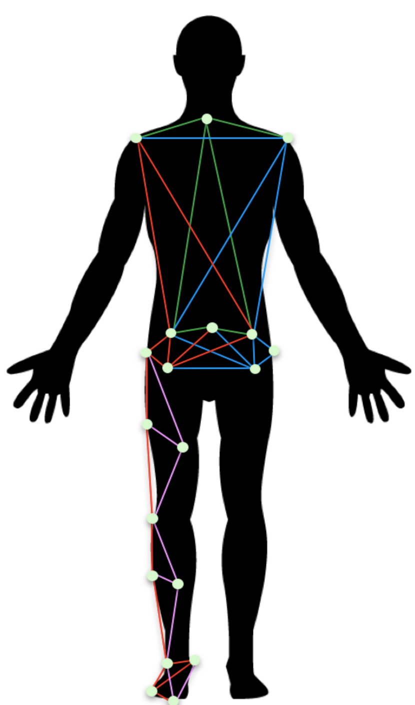
To measure and record subject's body movement, the Vicon MX motion capture system including eight cameras and four force platforms were used. 21 spherical-shaped retroreflective markers with an adhesive surface were attached to each subject's skin at anatomical points on right lower body, both shoulders, and shoes as shown in Figure 3.13 and Figure 3.14.



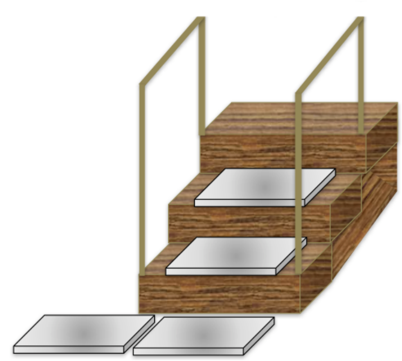
A. Front view with markers

B. Back view with markers

Figure 3.13. 21 Markers at subject's anatomical points created by the researcher.



B. Sustainable shoes (left) and leather shoes (right) with markers



A. Static motion connected with markers

C. Stairs with four force platform

Figure 3.14. Motion capture, shoe prototypes, and stairs created by the researcher.

Instruments for Wear Testing

To conduct participants' wear testing of shoes, the following equipment and software were used: (a) motion analysis systems (Vicon MX, Vicon, Centennial, CO) including eight cameras with Peak/Vicon Motus, video, optical, and analog capabilities and (b) two force platforms (Advanced Mechanical Technology Inc., Watertown, MA) that were positioned centrally on a 35-m walkway in a pit that is isolated. Motion capture and force platform data were collected concurrently at sampling frequencies of 160Hz and 1600Hz, respectively.

The walking speed was monitored with the motion capture using the horizontal component of a marker adhered to each joint on the participant's lower body. Speed order was varied between subjects and three trials were conducted at each speed. During walking trials, the walking speed was 5% of the target speed and the targeting of the force platform was visually identified to minimize bias at a biomechanics laboratory (see Figure 3.15).

Data Analysis Procedures

Eight camera motion analysis systems were used to track body movement, and four force platforms measured ground reaction force data. The motion capture data were used to determine joint range of motion. The motion capture data and force platform data were combined to determine forces and joint range of motion. After finishing the tests, all participants were asked to answer a short questionnaire, through Qualtrics software, regarding a consumer's acceptance of both men' sustainable dress shoes and leather dress shoes.

Kinematic and kinetic approaches using wear testing data. A paired samples *t*-test was used to determine mean differences in stance time, range of motion, ground reaction forces, and joint moment by comparing commercial leather shoes and sustainable shoes during normal walking, ascending stairs, and descending stairs randomly assigned three times. After Vicon Nexus software was set to determine marker tracking, MATLAB (Matrix Laboratory) was first performed to reduce both kinematic and kinetic data. The next step was to investigate comparison between leather shoes (M_L) and sustainable shoes (M_S) in three different conditions for the proposed hypotheses using SPSS software.

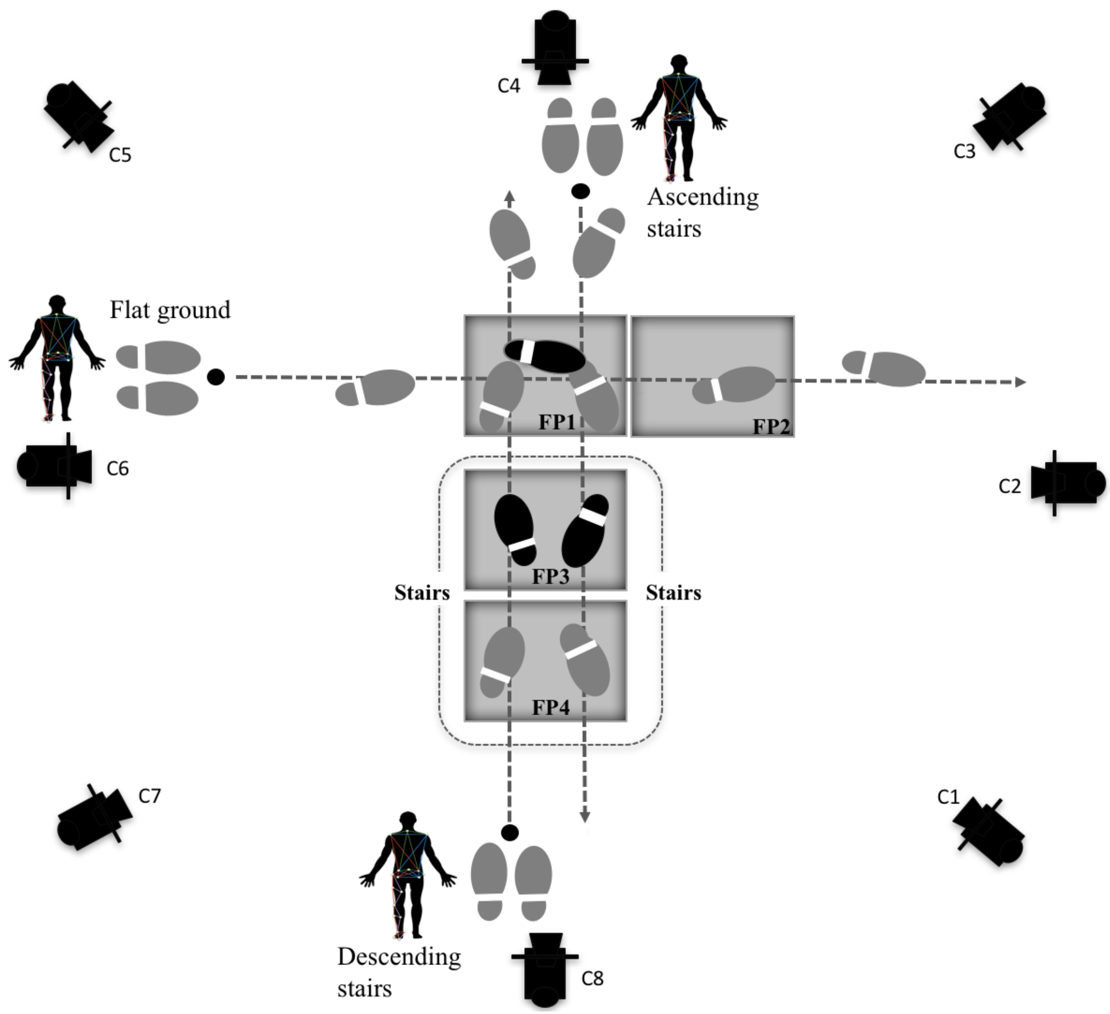


Figure 3.15. Directions of movements at the laboratory created by the researcher.

Note. C# = each camera number, FP# = force platform number.

Wear's Perceptions and Acceptance for Sustainable shoes

Objective 5 of this study was to assess wearers' perceptions and acceptance for the sustainable shoes comparing with the leather shoes via web-based survey (Qulatrics), after finishing the wear testing of both sustainable shoes and leather shoes. Figure 3.16 displays the overall wear testing protocol plan. The detail wear testing proposal was included in Appendix H.

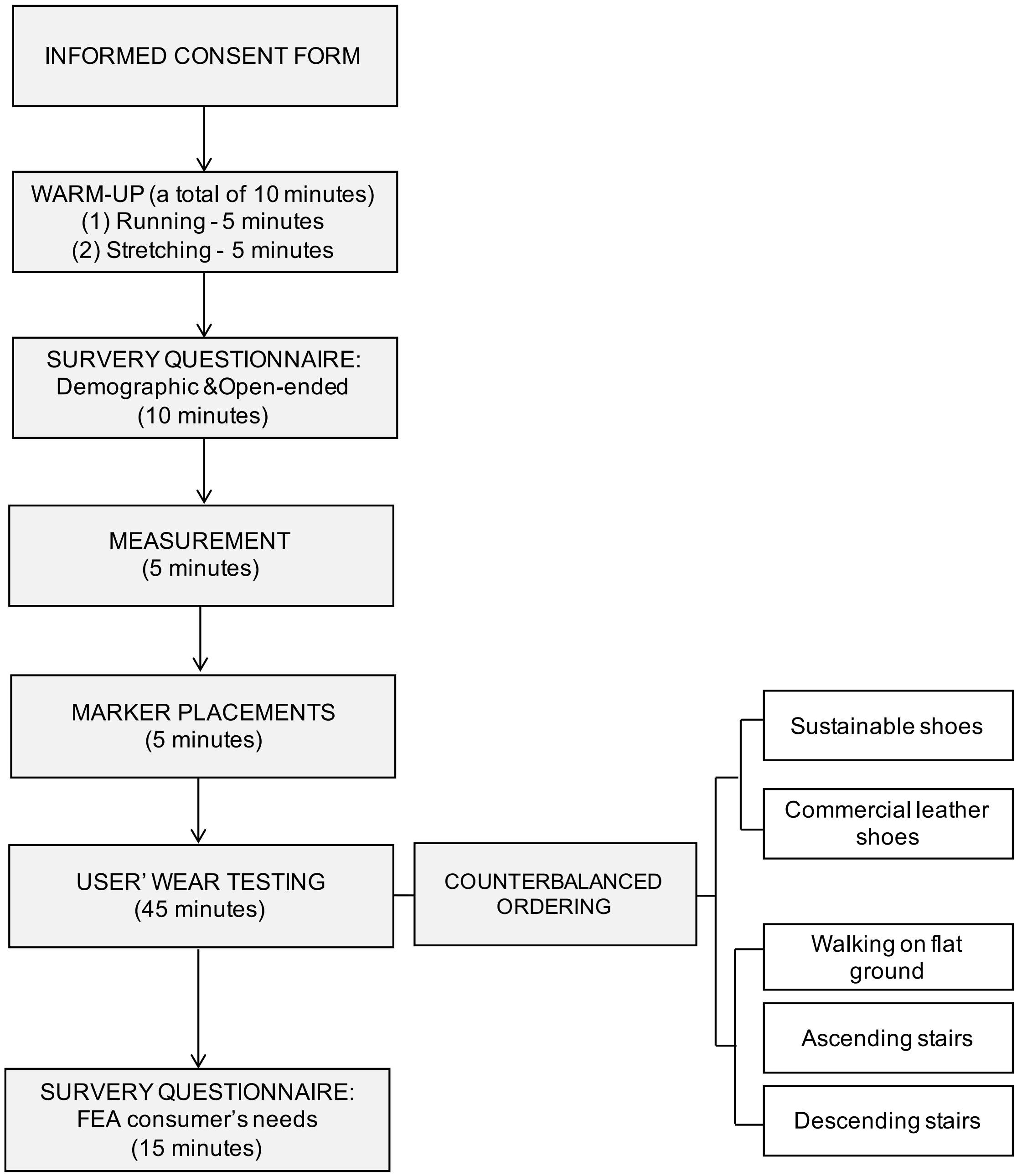


Figure 3.16. The overall wear testing protocol plan.

Survey questionnaire. The survey consisted of seven sections: Section 1: participants' demographic characteristics and key body measurements (ten items), Section 2: open-ended questions asking their thoughts of sustainable shoes and its benefit, experience, and reasonable price (seven items), Section 3: functional needs (nine items), Section 4: expressive needs (nine items), Section 5: aesthetic needs (nine items); Section 6: physical fit and comfort during the wear trials (eight items), and Section 7: wearer' acceptance modified from previous studies (four items, Au & Goonetileke, 2007; Cao et al. 2014b). Participants took the sections 3 to 7 in terms of FEA consumer needs for both sustainable shoes and leather shoes. The questions were measured using a five-point Likert-type scale, ranging from "very poor" (1) to "very good" (5) in sections 3 and 5; from "very dissatisfied" (1) to "very satisfied" (5) in section 4; and from "strongly disagree" (1) to "strongly agree" (5) in sections 6 and 7. Appendix K includes the questionnaire that was used for this study.

Survey data analysis. The data set collected from the survey was analyzed following three contents: (a) participants' open-ended questions using NVivo software, (b) participants' demographic questions using SPSS software, and (c) participants' perceptions and acceptance investigated comparison between commercial leather shoes and sustainable shoes in FEAMA model (functional, expressive, and aesthetic consumer's needs, mobility, and acceptance) for a paired sample *t*-test using SPSS software as well. The level of significance is set at $\alpha = 0.05$. Therefore, the following hypotheses were proposed and tested:

H5: There are significant mean differences between commercial leather shoes and sustainable shoes in overall FEAMA model.

H6: There are significant mean differences between commercial leather shoes and sustainable shoes in functional consumer's needs.

H7: There are significant mean differences between commercial leather shoes and sustainable shoes in expressive consumer's needs.

H8: There are significant mean differences between commercial leather shoes and sustainable shoes in aesthetic consumer's needs.

H9: There are significant mean differences between commercial leather shoes and sustainable shoes in mobility in three different conditions.

H10: There are significant mean differences between commercial leather shoes and sustainable shoes in wearer's acceptance.

Correlation coefficient. After completely finishing data collection, Pearson's (*r*) correlation coefficient ranging from +1 to –1 was measured for strength of a linear relationship among variables in material testing and wear testing, respectively. Evan (1996) suggested the guide with the absolute value of correlation coefficient (see Table 3.3).

Table 3.3. *Criteria of Correlation Coefficient*

Strength of relationship	Pearson's (*r*) correlation coefficient	
	Positive	Negative
Small	0.1 to 0.3	– 0.1 to – 0.3
Medium	0.3 to 0.5	– 0.3 to – 0.5
Large	0.5 to 1.0	– 0.5 to – 1.0

A summary of the research objectives and subjects, data, and statistics used in this study is listed in Table 3.4.

Table 3.4. *Methods Used for Data Analysis*

Purpose of Analysis	Subjects/ materials*	Data Used in Analysis	Statistics
Demographic description and open-end questions	42	Variables about personal • Personal information (5 items): birth year, ethnicity (web-based) shoes size, foot dominance, leg surgery experience (face-to-face)	Frequencies & percentages
		• Measurement (5 items): right and left foot, height, weight, test shoes sizes (face-to-face) • Open-end questions (7 items): 3 words, benefits, general features, FEA features, purchase experience, willingness, cost in terms of sustainable shoes	Descriptive statistics (mean and standard deviation)
Research objective 1: Design criteria identification		Target market and consumers Cultural context Cradle to cradle Functional-expressive-aesthetic needs, mobility, and acceptance	n/a

Table 3.4. *Continued*

Research objective 2: Material property examination	7*	• Thickness • Weight • Air permeability • Thermal resistance • Evaporative resistance • Total heat loss • Permeability • Evaporative potential • Break force • Elongation • Tensile strength • Elongation at break • Young's modulus • Load at break • Contact angle	*t*-test & ANOVA using SPSS
Research objective 3: Design & development of sustainable shoes		Stage 1: Problem identification & eco-material selection Stage 2: Eco-material assessment & prototype development	n/a
Research objective 4: Wear testing	37/42[a]	Stage 3: Wear testing & prototype evaluation Kinematic parameters H1. stance time H2. range of motion Kinetic parameters H3. ground reaction force H4. joint moments Three different walking motions (i.e., walking on flat ground, ascending stairs, descending stairs)	Paired simple *t*-test
Research objective 5: Survey	42	Perceived FEAMA measurement items: H5. overall FEAMA (8 items) H6. functional needs (9 items) H7. expressive needs (9 items) H8. aesthetic needs (9 items) H9. mobility (8 items) H10. acceptance (4 items)	Descriptive statistics (mean and standard deviation) *t*-test using SPSS

Note. * means material samples; 37/42 [a] means two missing data of a total of 42 human subjects; H = hypothesis

CHAPTER 4. RESULTS AND DISCUSSION

The overall purpose of this study was to investigate the compatibility of sustainable shoes made with BC non-woven mats integrating with eco-friendly materials (denim fabric, hemp fabric, compressed paper, and cork material), compared with durability and comfort in performance of newly developed sustainable shoes and commercially available leather shoes via users' wear testing. This study also examined wearers' perceptions and acceptance in the sustainable shoes, compared with leather shoes via survey questionnaire.

This chapter discusses the results of the four main studies: (a) proposed integrated theoretical footwear design framework (Study 1), (b) material evaluation (Study 2), (c) sustainable shoe prototypes (Study 3), and (d) wear testing including kinematic and kinetic approaches as well as wearers' perceptions and acceptance of men's sustainable shoes (Study 4).

Study 1: Proposed Integrated Theoretical Footwear Design Framework

This study used an integrated theoretical framework, the cradle-to-cradle design process for sustainable shoes, adapted from the following theoretical elements: The cradle-to-cradle (C2C) design model (McDonough & Braungart, 2002) and the functional-expressive-aesthetic (FEA) Consumer Need Model (Lamb & Kallal, 1992). In addition, this study adapted Anastas and Zimmerman's (2003) 12 principles of green engineering and incorporated these within the shoe development process to turn a sustainability practice vision into reality for footwear industry. Therefore, the proposed integrated theoretical framework, combining the FEA consumer's need model and C2C design process model integrated five principles (1, 2, 7, 10, and 11), is a feasible design framework for developing a sustainable footwear (product development) design and process (see Figure 4.1). Ultimately, this framework enables designers, educators, and manufacturers to understand the target consumers' needs, to enhance awareness of environmental issues, and to urge them to easily and fully implement sustainability practices into new sustainable product design and development processes.

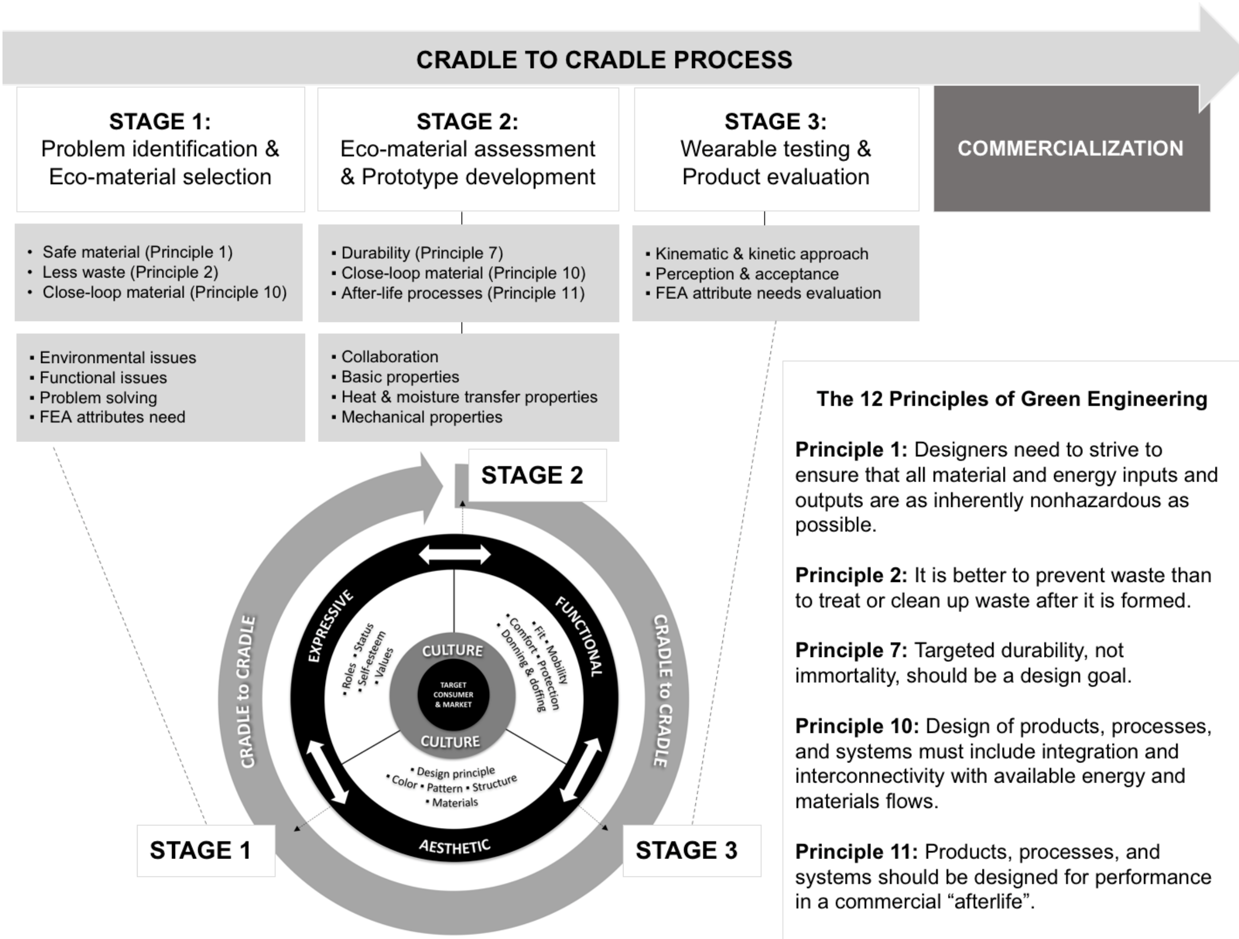


Figure 4.1. The proposed integrated theoretical framework.

Study 2: Material Evaluation of Sustainable Shoes

To develop a biodegradable and compostable material that could be used as a leather alternative material for the footwear industry, we proposed MCM and examined its properties compared with those of MCPL, a product often used when making shoes. After exploring the properties of five single-layered materials, those constituting two multi-layered materials (MCM and MCPL) were examined in the objectives of Study 2. Therefore, the material testing results were proposed to obtain the similar properties of MCM and MCLP.

Physical Properties: Thickness, Weight, and Air Permeability

The mean (M) and standard deviation (SD) of thickness, weight, and air permeability for the five single-layered materials are presented in Table 4.1 For the single-layered materials, non-woven calf-skin leather was discovered to be the thickest (1.5mm) and the heaviest (275g), with the lowest air permeability (0.003cfm). By contrast, plain weave hemp fabric was the thinnest (0.51mm) and the lightest (38g) among the materials, and demonstrated the highest air permeability (703cfm). The non-woven materials (i.e., calf-skin leather, BC non-woven mat, pig-skin leather) showed greater thickness and weight and were almost impermeable, while the materials with woven structures (i.e., denim and hemp fabrics) showed less thickness and lower weight and were permeable to air. The thickness (except denim fabric and pig-skin leather) and weight were significantly different among single-layered materials. Hemp fabric showed the only statistically significant mean differences in comparison with other materials for air permeability ($p < 0.05$).

Table 4.1. *Physical Properties for Single-Layered Materials*

Type of materials	Thickness (mm)		Weight (g)		Air permeability (cfm)	
	Mean ± SD	F-value	Mean ± SD	F-value	Mean ± SD	F-value
		1020.8***		10341.1***		1868.26***
BC non-woven mat	1.15 ± 0.03		121.7 ± 1.7		0.24 ± 0.05	
Denim fabric	0.75 ± 0.01		81.7 ± 2.4		17.37 ± 0.35	
Hemp fabric	0.51 ± 0.02		38.0 ± 1.3		703 ± 28	
Calf-skin leather	1.50 ± 0.02		275.3 ± 0.9		0.003 ± 0.00	
Pig-skin leather	0.80 ± 0.01		164.7 ± 0.8		0.006 ± 0.00	

Note. *F*-value for Turkey HSD test for single-layered; SD = standard deviation; ***$p < 0.001$, two-tailed.

As shown in Table 4.2, the thickness of MCM and MCPL was equal to 2.26mm; however, the weight of MCM (241g) was almost twice as light as the weight of MCPL (440g, $t = -973.66$, $p < 0.001$). In the multi-layered arrangement, statistically significant mean differences were found between MCM and MCPL ($t_{front} = 17.67$, $p < 0.01$; $t_{back} = 5.55$, $p < 0.05$) on double sides in terms of air permeability; this is because of the different structures on the front and backside of MCM, consisting of the BC non-woven mat on the front side (less air permeability) and woven structured hemp fabric on the backside (high air permeability). MCM can be potentially used as an entire shell for sustainable shoes instead of calf- and pig-skin leathers, due to its lightness and air flow capability. Examining the basic properties of materials helped to select appropriate materials for the sustainable footwear design and development and demonstrated the influence of these properties on its design and development process.

Table 4.2. *Physical Properties for Multi-Layered Materials*

	Thickness (mm)		Weight (g)		Air permeability (cfm)	
Type of materials	Mean ± SD	*t*-value	Mean ± SD	*t*-value	Mean ± SD	*t*-value
		0.056		-973.66***		17.67**
MCM front	2.26 ± 0.10		241.4 ± 0.3		2.10 ± 0.10	
MCPL front	2.26 ± 0.04		439.7 ± 0.2		0	
						5.55*[a]
MCM back					0.07 ± 0.02	
MCPL back					0	

Note. *t*-value for an independent sample t-test for multi-layered materials; MCM = a multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; SD = standard deviation; **p* < 0.05; ***p* < 0.01; ****p* < 0.001, two-tailed.

Heat and Moisture Transfer Properties

The thickness, weight, and air permeability of materials or fabrics have influences on thermal (R_{ct}) and water vapor resistance (R_{et}) properties.

Thermal and water vapor resistance. The results of thermal and evaporative resistances (R_{ct} and R_{et}) for single-layered materials are also shown in Table 4.3. Among the single-layered materials, the BC non-woven mat was found to have the lowest R_{ct} ($0.081 m^2 \cdot {}^{o}C/W$) and hemp fabric, the material with the lowest thickness and highest air permeability, was found to have the lowest R_{et} ($9.57 m^2 \cdot Pa/W$); low R_{ct} and R_{et} properties generally outperform the thermal comfort of materials in terms of potential total heat loss, and permeability index (Huang, 2006; McQuerry et al., 2017, Yoo & Barker, 2005). In addition, there were no statistically significant mean differences between denim fabric and hemp fabric in evaporative resistance, because both fabrics has the same woven structure and liquid permeable properties. However, there were statistically significant mean differences among single-layered materials ($p < 0.001$) in R_{ct} ($F = 145.02$) and R_{et} ($F = 1627.32$). This result demonstrates different properties among the single-layered materials in thermal and evaporative resistances.

Table 4.3. *Heat and Moisture Transfer Properties for Single-Layered Materials*

Type of materials	Thermal resistance (R_{ct}, °C·W/m^2)		Evaporative resistance (R_{et}, Pa·W/m^2)	
	Mean ± SD	*F*-value	Mean ± SD	*F*-value
		145.02***		1627.32***
BC non-woven mat	0.081 ± 0.000		53.71 ± 2.96	
Denim fabric	0.094 ± 0.001		10.88 ± 0.33	
Hemp fabric	0.111 ± 0.003		9.57 ± 0.17	
Calf-skin leather	0.091 ± 0.001		147.24 ± 4.42	
Pig-skin leather	0.087 ± 0.001		49.92 ± 0.68	

Note. *F*-value for Turkey HSD test for single-layered; MCM = a multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; SD = standard deviation; ***$p <$ 0.001, two-tailed.

For the multi-layered materials, MCM's R_{ct} (0.12m^2·°C/W) was slightly higher, while the value for R_{et} (117.71m^2·Pa/W) was lower than those of MCPL (see Table 4.4); this is because the inner layer's inverse property showed the highest thermal and lowest evaporative resistance (Huang, 2006; McQuerry et al., 2017).

Table 4.4. *Heat and Moisture Transfer Properties for Multi-Layered Materials*

Type of materials	Thermal resistance (R_{ct}, °C·W/m^2)		Evaporative resistance (R_{et}, Pa·W/m^2)	
	Mean ± SD	*t*-value	Mean ± SD	*t*-value
		8.44***		-12.43***
MCM	0.120 ± 0.001		117.71 ± 5.60	
MCPL	0.107 ± 0.002		180.94 ± 6.81	

Note. *t*-value for an independent sample t-test for multi-layered materials; MCM = a multi-layered cellulosic material including cellulous BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; SD = standard deviation; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$, two-tailed.

Consequently, permeable materials are closely related to higher R_{ct} and lower R_{et} in comparison to impermeable materials. Statistically significant mean differences in R_{ct} ($t = 8.44$) and R_{et} ($t = -12.43$) were found between MCM and MCPL ($p < 0.001$), potentially an influence of the air gaps among single-layered materials.

Total heat loss and permeability index. The results for the total heat loss (THL) and permeability index (i_m) were calculated from R_{ct} and R_{et} for single-layered and multi-layered materials; the findings are displayed in Table 4.5, respectively. The findings demonstrated that THLs in individual eco-layered materials (i.e., BC non-woven mat, denim fabric, hemp fabric) were higher than those of individual calf-skin leather and pig-skin leather. However, despite the greater mean differences among single-layered material's THLs ($F = 1572.92$, $p < 0.001$), no statistically significant mean differences ($t = -1.85$) in THL were found between MCM (153.9W/m^2) and MCPL (158.4W/m^2); this can be interpreted as the inner layer, hemp fabric, possibly providing the greatest heat loss of the three-layered configuration of BC non-woven mat, denim fabric, and hemp fabric. Indeed, properties of the inner layer can be an important factor in a multi-layered footwear system (McQuerry et al., 2017). Both MCM and MCPL with the similar THL values allowed heat dissipation through heat and moisture transfer to the environment.

Based on the permeability index (i_m; Woodcock, 1962), ranging from "utterly water vapor impermeable" (0) to "completely water vapor permeable" (1), hemp fabric yielded the highest value of i_m (0.70), followed by denim fabric (0.53) and pig-skin leather (0.11), as shown in Table 4.5. The differences between MCM (0.06) and MCPL (0.04) in i_m were found to be statistically significant ($t = 13.21$, $p < 0.001$); thus, it can be argued that MCM with a higher i_m value performs better than MCPL in terms of the permeability index (Woodcock, 1962). Thus, footwear designers and developers will be able to create sustainable products using MCM. In terms of thermal comfort, the key factor should be the material's property, because the BC non-woven mat has a good heat conductor, while leather as a protein has an excellent heat retention. Further research needs to be conducted to confirm this prediction through human trials.

Table 4.5. *Total Heat Loss and Permeability Index*

Type of materials	Total Heat Loss (THL, W/m^2)		Permeability Index (i_m)	
	Mean ± SD	*F* or *t*-value		*F* or *t*-value
Single-layered		1572.92***[a]		2170.36***[a]
BC non-woven mat	248.04 ± 3.79		0.091 ± 0.01	
Denim fabric	469.49 ± 10.08		0.525 ± 0.02	
Hemp fabric	488.16 ± 8.29		0.702 ± 0.02	
Calf-skin leather	188.19 ± 0.93		0.037 ± 0.00	
Pig-skin leather	240.29 ± 1.84		0.106 ± 0.00	
Multi-layered		-1.85[b]		13.21***[b]
MCM	153.89 ± 2.21		0.062 ± 0.00	
MCPL	158.37 ± 3.57		0.036 ± 0.00	

Note. [a] *F*-value for Turkey HSD test for single-layered; [b] *t*-value for an independent sample *t*-test for multi-layered materials; MCM = a multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; R^2 = coefficient of determination indicating the strength of the relationship between i_m and clo in the regression line; ****p* < 0.001, two-tailed.

Evaporative potential. Evaporative potential (EP) is able to indicate whether or not the wearer potentially has heat stress associated with wear's comfort and performance (Chang & Gonzalez, 1999). Table 4.6 displays a comparative analysis result of the material's permeability index (i_m), clothing insulation (clo), and coefficient of determination (R^2), indicating the strength of the relationship between i_m and clo. These results illustrate that denim fabric has a strong relationship (0.98), while both BC non-woven mat and pig-skin leather have a weak relationship (0.25), between i_m and clo. A stronger relationship of MCM (0.89) was established between i_m and clo over that of MCPL (0.79).

The EP over a certain value (0.28) could possibly yield benefits to wearers of footwear (e.g., potential reduction zone of heat stress); however, the EP's value below 0.15 may cause significant deterioration of evaporative heat from the wearer's product (Aoyagi, McLellan, & Shephard, 1994; Chang & Gonzalez, 1999). The EP of most single-layered materials, with the exception of calf-skin leather (0.27), lies above 0.28, meaning in a beneficial evaporation zone. For the multi-layered materials, however, the EP values of MCM (0.22) and MCPL (0.19) presented the evaporation zone (0.15 < EP < 0.28). This result can be explained as in the zone heat acclimation is impossible to reduce heat strain experienced by the wearers. Therefore, further research is needed to identify the EP regarding footwear within this zone, because of considering the importance of understanding the EP of materials for sustainable shoe design.

Table 4.6. *Evaporative Potential and R^2*

Type of materials	Clothing insulation (clo)		Evaporative potential (i_m/clo)	
	Mean ± SD	*F* or *t*-value		R^2
Single-layered		139.41***[a]		
BC non-woven mat	0.032 ± 0.00		2.84	0.25
Denim fabric	0.114 ± 0.01		4.61	0.98
Hemp fabric	0.221 ± 0.02		3.18	0.88
Calf-skin leather	0.138 ± 0.01		0.27	0.81
Pig-skin leather	0.064 ± 0.01		1.66	0.25
Multi-layered		8.22***[b]		
MCM	0.280 ± 0.01		0.22	0.89
MCPL	0.193 ± 0.02		0.19	0.79

Note. [a] *F*-value for Turkey HSD test for single-layered; [b] *t*-value for an independent sample t-test for multi-layered materials; MCM = a multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; R^2 = coefficient of determination indicating the strength of the relationship between i_m and clo in the regression line; ***$p < 0.001$, two-tailed.

Mechanical Properties

For examining the tensile strength, the breaking strength and elongation of seven samples (five single-layered and two multi-layered materials) were evaluated three times with following the ASTM D-5034 method. To further analyze the tensile strength, the Instron instrument was implemented three times to determine tensile strength, elongation at break, Young's modulus, and load at break of the seven samples, according to the ASTM D-882 method.

Tensile properties (ASTM D-5034). As shown in Figure 4.2, for single-layered materials, calf-skin leather showed the greatest values in break force (2243N), followed by the BC non-woven mat (1425N), denim fabric (1236N), pig-skin leather (720N), and hemp fabric (607N). Non-woven materials showed greater tensile strength than woven materials, but weave pattern formation (e.g., plain weave) and density cause enhancement of tensile strength (Adekunle, Cho, Patzelt, Blomfeldt, & Skrifvars, 2011).

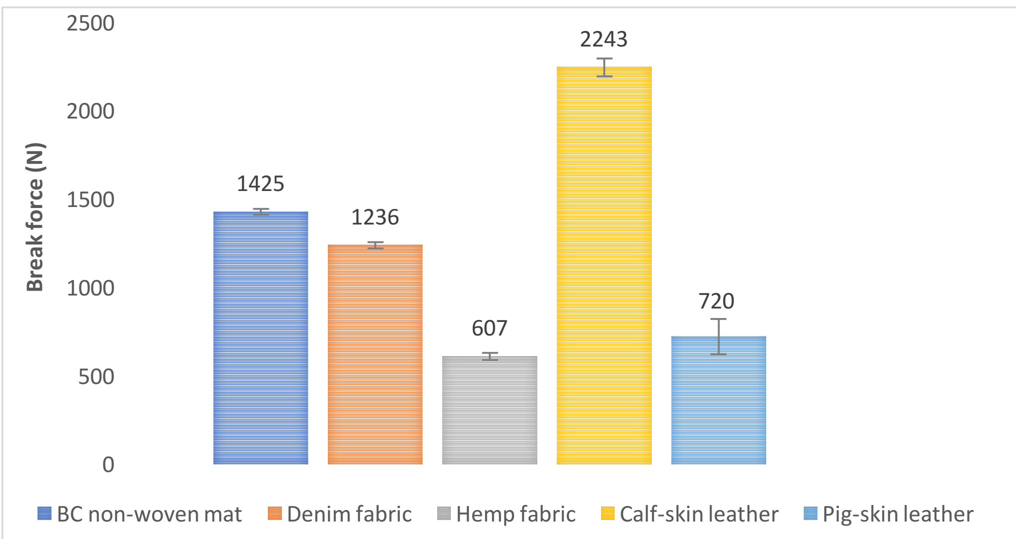


Figure 4.2. Five single-layered materials tested for break force.

The findings indicated that the break force of hemp fabric is not different from that of pig-skin leather. Hemp fabric can be effective for use as an inner shell of shoes, because the pig-skin leather is commonly applied to inner shells of leather shoes. The break forces for calf-skin leather were significantly different among the other single-layered materials.

As shown in Figure 4.3, denim fabric yielded the highest value in elongation (34%) followed by BC non-woven mat (29%), pig-skin leather (28%), calf-skin leather (23%), and hemp fabric (6%). Woven material with high density provide great elongation values than non-woven material so that degree of density can influence elongation of materials.

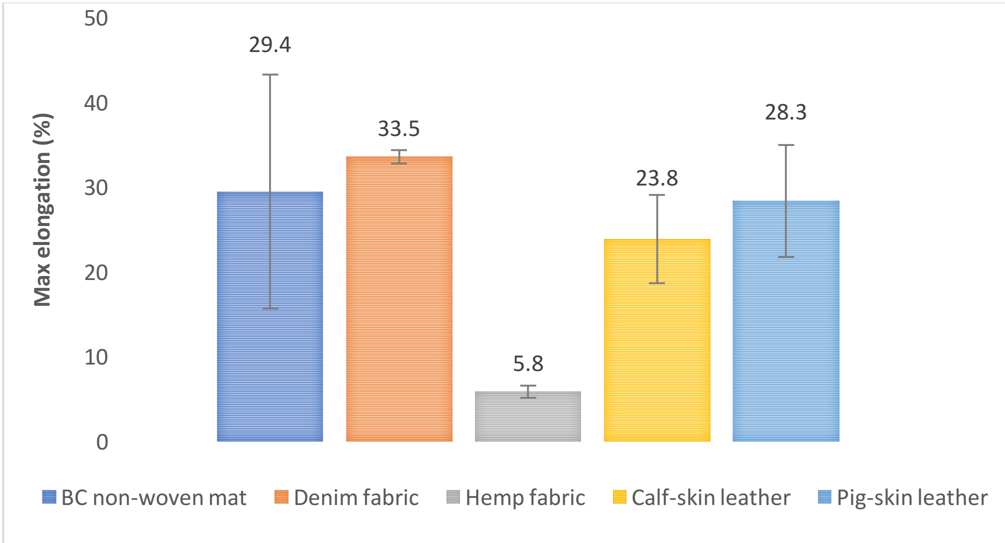


Figure 4.3. Five single-layered materials tested for max elongation.

As shown in Table 4.7, no significant mean differences were found between the BC non-woven mat and denim fabric in break force and elongation. This can be explained in that both materials have similar tensile strength, and denim fabric is more ideal for enhancing tensile strength of the BC non-woven mat as a middle layer in MCM. However, the mean differences among the single-layered materials for both break force (F = 94.46) and elongation (F = 14.25) were found to be statistically significant (p < 0.001).

As exhibited in Figure 4.4 and Table 4.7, results of tensile properties demonstrated that MCPL produced the higher value in break force (3591N) than that of MCM (3486N). However, no statistically significant differences were found between MCM and MCPL in break force (t = - 0.53). It is likely that denim fabric contributes to the tensile strength of MCM; this can be interpreted that MCM and MCPL have a similar level of break force. MCPL had the higher value in elongation (55%) compared to that of MCM (27%); statistically significant differences were found between MCM and MCPL (t = -6.69; p < 0.01), because hemp fabric, along with its stiff properties, indicated a very low break force and elongation; this stands in opposition to the found break force and elongation values of other materials, as both the leathers showed flexibility with the high elongation values.

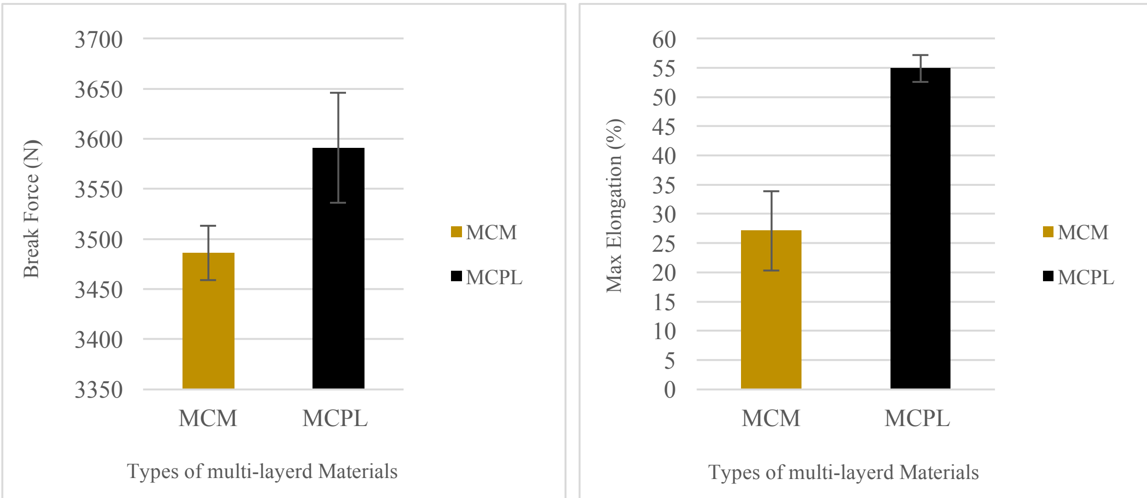


Figure 4.4. Break force (left) and max elongation (right) of MCM and MCPL fabrics.
Note. A multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric (MCM); calf- and pig-skin leather (MCPL).

Therefore, results of an analysis of the single-layered materials could assist in decision-making about the arrangement of each material in MCM in order to increase its tensile strength.

Table 4.7. *Tensile Strength with ASTM D-5034 Method*

Type of materials	Break force (N)		Max elongation (%)	
	Mean ± SD	*F* or *t*-value	Mean ± SD	*F* or *t*-value
Single-layered		94.46***[a]		14.25***[a]
BC non-woven mat	1425 ± 15.8		29.4 ± 13.8	
Denim fabric	1236 ± 19		33.5 ± 0.8	
Hemp fabric	607 ± 20.3		5.8 ± 0.7	
Calf-skin leather	2243 ± 50		23.8 ± 5.2	
Pig-skin leather	720 ± 100		28.3 ± 6.6	
Multi-layered		-0.53[b]		-6.69**[b]
MCM	3486 ± 27.1		27.1 ± 6.8	
MCPL	3591 ± 54.9		54.9 ± 2.3	

Note. [a] *F*-value for post-hoc comparisons with Turkey HSD test for single-layered; [b] *t*-value for an independent sample t-test for multi-layered materials; MCM = a multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; R^2 = coefficient of determination indicating the strength of the relationship between *im* and clo in the regression line; $^{**}p < 0.01$; $^{***}p < 0.001$, two-tailed.

Tensile property (ASTM D-882). The tensile strength properties of single-layered and multi-layered materials were measured from typical tensile stress and strain curves, as illustrated in Figure 4.5. The tensile stress of calf-skin leather was substantially higher than other materials. Also, the tensile stress of MCPL with a smooth line was greater than MCM, due to individual different structures (e.g., non-woven and woven) with MCM.

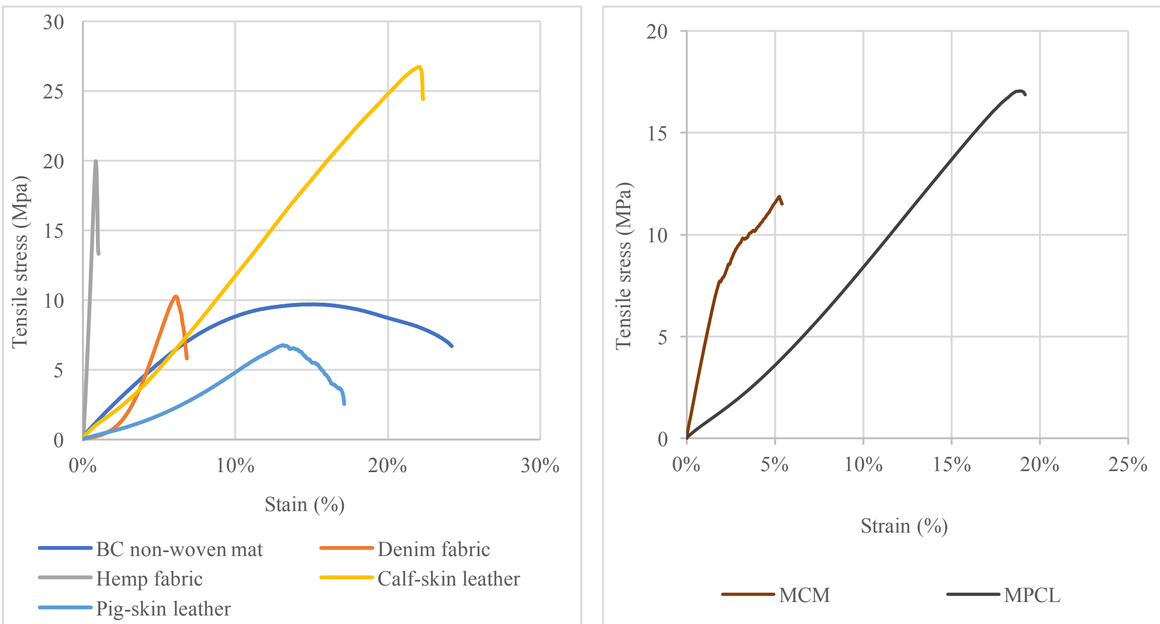


Figure 4.5. Tensile stress curves of single-layered and multi-layered materials.
Note. A multi-layered cellulosic material including BC non-woven mat, denim fabric, and hemp fabric (MCM); calf-skin and pig-skin leathers (MCPL).

The mechanical properties of single-layered and multi-layered materials are presented in Table 4.8. The calf-skin leather had the highest tensile strength (24.7Mpa), elongation at break (23%), and Young's modulus (1081MPa), while tensile strength (7.1Mpa), Young's modulus (76 MPa), and load at break (73.8N) of the pig-skin leather were the lowest. It can be inferred that the outer shell (i.e., calf-skin leather) of commercial leather shoes should be stronger than the inner shell (i.e., pig-skin leather). Although natural fibers can assist in increasing the strength and stiffness and also reducing the weight of the resulting bio-composite materials (Khanam, Reddy, Raghu, & Naidu, 2010), MCM is less stiff and a more flexible material compared to MCPL, with the findings showing low tensile strength, Young's modulus, and elongation at break values associated with flexibility (Garcia, Pinotti, & Zaritzky, 2006).

For multi-layered materials, there were statistically significant mean differences between MCM and MCPL ($p < 0.05$) in tensile strength (t = -4.07), elongation (t = -11.82), and Young's modulus (t = -4.59), but no significant mean differences between MCM and MCPL in load at break. It can be explained that different properties of single-layered materials may be attributed to the mechanical properties of MCM and MCPL.

Table 4.8. *Tensile Strength with ASTM D-882 Method*

Type of materials	Mean ± SD			
	Tensile strength (MPa)	Elongation at break (%)	Young's Modulus (MPa)	Load at Break (N)
Single-layered	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
BC non-woven mat	8.7 ± 1.7	22 ± 2.1	202.2 ± 53.7	110.3 ± 9.8
Denim fabric	9.8 ± 0.5	6.7 ± 0.1	133.0 ± 15.7	319.2 ± 2.6
Hemp fabric	15.2 ± 1.2	2.9 ± 0.2	158.9 ± 8.7	1119.7 ± 147.8
Calf-skin leather	24.7 ± 2.0	22.7 ± 0.6	1081.1 ± 96.2	120.5 ± 18.1
Pig-skin leather	7.1 ± 1.0	18.7 ± 2.1	76.0 ± 22.9	73.8 ± 15.5
Multi-layered	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
MCM	12.6 ± 2.3	6.2 ± 0.8	780.8 ± 135.5	515.6 ± 180.6
MCPL	18.4 ± 0.8	21.3 ± 2.1	1191.4 ± 75.0	106.6 ± 9.4
F or *t*-value				
Type of materials	Tensile strength (MPa)	Elongation at break (%)	Young's Modulus (MPa)	Load at Break (N)
Single-layered	82.84***[a]	137.65***[a]	206.1***[a]	129.9***[a]
Multi-layered	-4.07*[b]	-11.82***[b]	-4.59**[b]	3.92[b]

Note. [a] *F*-value for Turkey HSD test for single-layered; [b] *t*-value for an independent sample t-test for multi-layered materials; MCM = a multi-layered cellulosic material including non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; SD = standard deviation; * means $p < 0.05$; *** means $p < 0.001$, two-tailed.

The thickness property of the overall samples has strong correlations among break force, tensile strength, Young's modulus, and load at break. The thickness has a significant positive effect on these properties, but negative effect on load at break (see Table 4.9). Consequently, the results of tensile properties using the Instron instrument with the ASTM D-882 method showed no statistically significant mean differences between MCM and MCPL compared with use of tensile testing equipment with ASTM D-5034, due to the thickness of the sample for stress-stain.

Table 4.9. *Correlations Among Tensile Strength Properties*

	Thickness	Break force	Max Elongation	Tensile strength	Elongation at break	Young's modulus	Load at break
Thickness	1						
Break force (ASTM 5034)	0.98**	1					
Max Elongation (ASTM 5034)	0.58**	0.60**	1				
Tensile strength (ASTM 882)	0.38	0.44*	0.46*	1			
Elongation at break (ASTM 882)	0.28	0.20	0.68**	0.24	1		
Young's modulus (ASTM 882)	0.84**	0.86**	0.70**	.81**	0.39	1	
Load at break (ASTM 882)	-0.37**	-0.25	-0.72**	0.05	-0.82**	-0.26	1

Notes. * means that correlation is significant at the 0.05 level; ** means that correlation is significant at the 0.01 level two-tailed.

Wettability property. The contact angle (CA, º) for wettability of the single-layered materials was measured with a water droplet on the surface of each single-layered material using OCA 20 sensitive machine camera system, which provides accurate reproducible images of water droplets on its surface (see Figure 4.6). As shown in Table 4.10, for the single-layered materials, the BC non-woven mat and the hemp fabric had the similar low values of CA (47°; 48°, respectively), but the water droplets quickly spread out. The calf-skin leather had the highest value of CA (88°), followed by the denim fabric (77°) and the pig-skin leathers (73°). Moreover, higher CA values are mostly caused by non-woven structures rather than woven structures of materials with respect to water wettability (Premkumar & Thangamani, 2017). However, the CA of BC non-woven mat was lower than CA of denim fabric. This result can be explained by the BC non-woven mat potentially being naturally grown with an even surface, resulting in both leathers having a less hydrophobic surface. Indeed, the CA of woven materials (denim and hemp fabrics) resulted in a value higher than 90°. The woven fabrics might cause the generation of a higher degree of CA with their hydrophilic surfaces (Zhang et al., 2013), because fuzz on the woven fabrics (finished commercial materials) helps to sustain water drops for some time, and then gradually spreads into the materials with nearly 0° of CA. Consequently, the CA of each single-layered material has statistically significant differences was found ($F = 25.77$, $p < 0.001$).

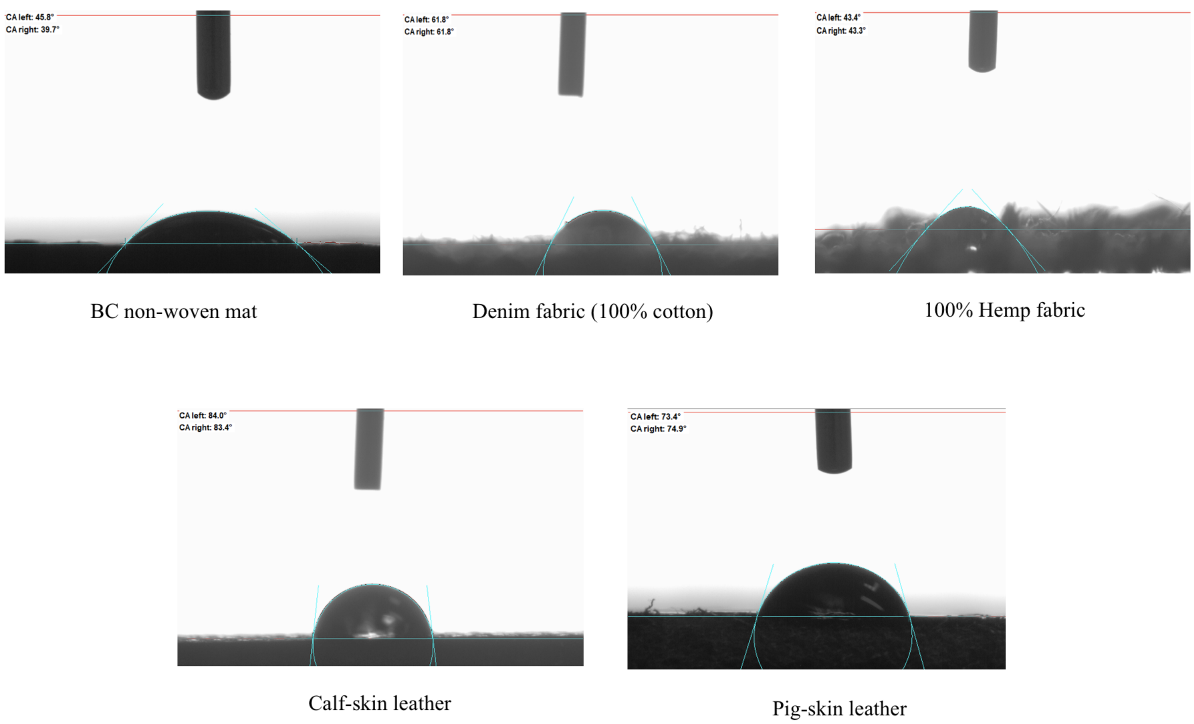


Figure 4.6. Contact angles of each single-layered material using OCA 20 camera.

The CA of the multi-layered materials with front and backsides is also presented in Table 4.10. The CA of $MCPL_{front}$ (84°) was much higher than that of MCM_{front} (31°); however, both materials had less than CA of 90°, due to the hydrophobicity of each material surface in terms of wettability. The CA of $MCPL_{back}$ (72°) was higher than that of MCM_{back} (60°), because the inner layer (the backside) of the MCM consists of plain and twill structures (hemp and denim fabric), while that of MCPL was a non-woven structure (pig-skin leather). Therefore, statistically significant mean differences were found between the two materials' front surfaces (t_{front} = -20.76 $p < 0.001$). These results indicate that different structures of MCM significantly influence wettability, due to an increase in CA values of MCM's inner layer (backside).

Table 4.10. *Contact Angles for Wettability*

	Contact angle (°)	
Type of materials	Mean ± SD	*F* or *t*-value
Single-layered		25.77***[a]
BC non-woven mat	46.9 ± 0.9	
Denim fabric (100% cotton)	76.6 ± 12.8	
Hemp fabric	47.7 ± 4.0	
Calf-skin leather	88.1 ± 2.8	
Pig-skin leather	73.1 ± 2.6	
Multi-layered front		-20.76***[b]
MCM front	30.6 ± 3.4	
MCPL front	83.6 ± 2.8	
Multi-layered back		-1.940[b]
MCM back	60.0 ± 8.1	
MCPL back	72.3 ± 7.4	

Note. [a] *F*-value for Turkey HSD test for single-layered; [b] *t*-value for an independent sample *t*-test for multi-layered materials; MCM = a multi-layered cellulosic material including non-woven mat, denim fabric, and hemp fabric; MCLP = calf- and pig-skin leathers; SD = standard deviation; ***$p < 0.001$, two-tailed.

Summary of Material Evaluation

In objective 3, the hypotheses were that these two materials would be similar properties. No significant mean differences were found between MCM and MCPL in physical properties, heat and moisture transfer properties, and mechanical properties. Thus, MCM can be potentially used as an entire shell for sustainable shoes instead of the both leathers, due to its lightness and air flow capability. The findings of this study support the effectiveness of MCM for use as a leather alternate when developing eco-friendly shoes, and provide insights to the footwear industry.

Study 3: Sustainable Shoe Prototypes

For this study, a total of five pairs of shoe prototypes made of MCM for wear testing were developed, with three different sizes of men's shoes: US size 9.5, 10, and 10.5 respectively and two extra shoes (US size 10 and 10.5) by the researcher after achieving objective 1 and 2. On the other hands, the commercial leather shoes made of high quality leathers, with a retail cost of approximately $80-100 and the same three sizes of the sustainable shoe prototypes by professional shoe makers in a small company. For example, the outer shell including upper (vamp), tongue, and quarter part of shoes was made of using two different leather colors (i.e., black and burgundy) and high quality of leather commonly. The shoe makers made the leather shoes following my own shoe patterns and design of the prototype provided by the researcher in order to perform wear testing (Objective 4 and 5), comparing the sustainable shoes with leather shoes through human wear trials at a kinesiology laboratory.

Study 4: Wear Testing (Kinematic and Kinetic Approaches)

The objective of Study 4 was to evaluate wearers' performance in men's leather shoes comparing with the sustainable shoes using an experimental research design. The hypotheses were no mean differences in kinetic and kinematic parameters of gait within lower extremity of participants when wearing two different shoes, while performing the following three conditions: walking on flat ground, ascending stairs, and descending stairs using a paired simple *t*-test.

A total of 42 human subjects were recruited. The participants first performed a warm-up protocol and completed a short web-based survey questionnaire eliciting participants' demographic characteristics. Their body measurements (i.e., weight, height, and foot) were then obtained. Each participant wore both the leather shoes (M_L) and sustainable shoes (M_S) prototypes and then performed the three conditions given, based on counterbalanced ordering (see Appendix I) to control order effects in this experimental research design. However, missing retroreflective markers were found from five participants during wear testing. Of the 42 participants, 37 usable human subjects were successfully obtained and analyzed for wear testing including the kinematic and kinetic approaches.

Study Participants

A total of 37 healthy male subjects (age 25 ± 7 years; height 1.75 ± 0.05m; mass 77.54 ± 11.50kg) including Asian (*n* = 19), followed by Caucasian/European American (*n* = 16) and Hispanic American/Latino (*n* = 2) without any history of legs and foot surgery or injury were obtained. Using G-power software, the sample size reached a 0.84 power level with an effect size (Cohen's $d = 0.5$) at $p < 0.05$ for post-hoc power analysis (see Figure 4.7).

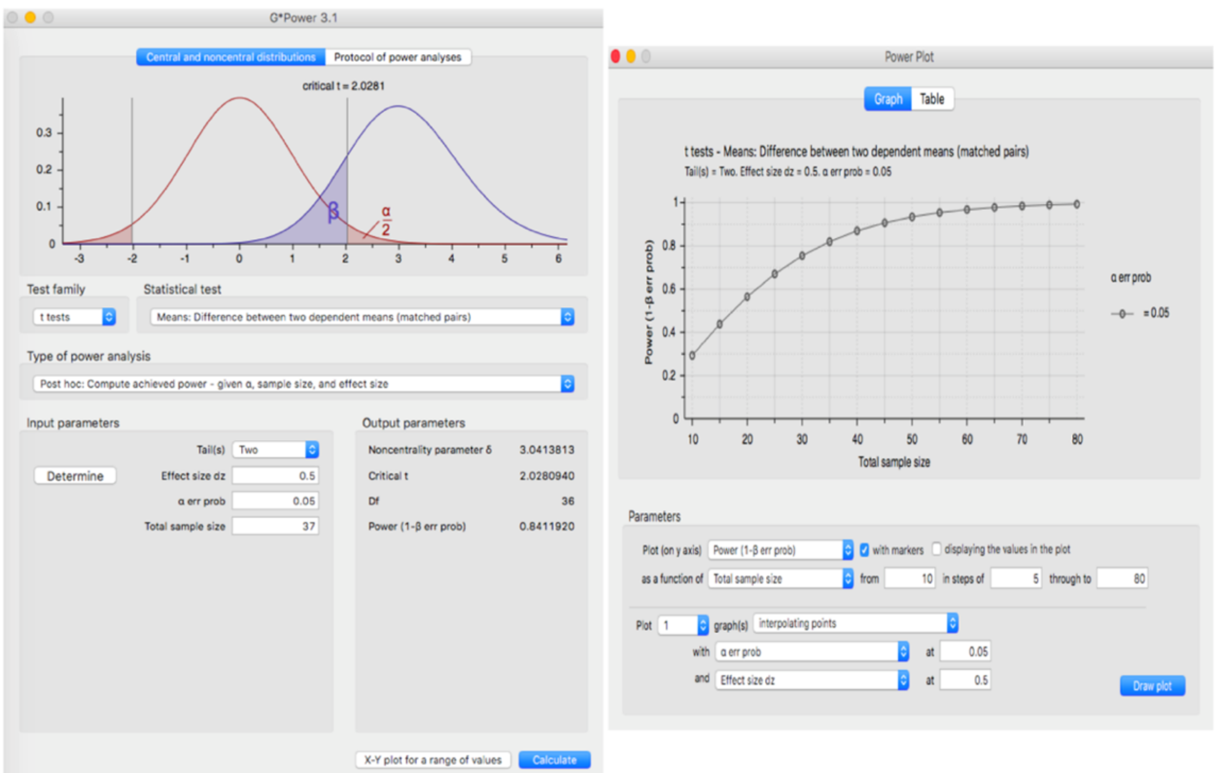


Figure 4.7. Post hoc power analysis of the paired simple t-test using G-power software.

Foot Morphology and Measurement

Foot morphology. All human subjects (n = 37) had dominant/preference foot (e.g., what foot they do use during kicking a ball) with right. Participant's feet were measured using foot-measuring device (The Genuine Brannock Device®), which has dual calibrations for length (heel to toe) and width measurements for US shoe sizes (see Table 4.11). The participants with right dominant foot had longer length and width than that of the left foot.

Table 4.11. *Human Subjects' Foot Measurements Using US Shoe Sizes*

	Left foot[a]	Right foot[b]	Paired Sample *t*-Test		
	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Length (US shoe size)	9.49 ± 1.0	9.85 ± 0.8	0.37 ± 0.5	4.615	0.000***
Width (US shoe size)	10.01 ± 1.2	10.04 ± 1.2	0.03 ± 0.5	0.489	0.744

Note. SD = standard deviation; MD = mean difference (b-a); ***$p < 0.001$; Sig.= significant two-tailed.

Shoes measurements. As shown in Table 4.12, based on three shoes size's measurement, there were no mean differences between length and width of the sustainable shoes and leather shoes; however, there were significant mean differences in weight of sustainable shoes (607.9g) and leather shoes (745.9g), respectively (MD = -138.0, $p < 0.05$).

Table 4.12. *Measurements of Leather and Sustainable Shoes*

	Leather shoes[a]	Sustainable shoes[b]	Paired Sample *t*-Test		
	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Length (cm)	30.8 ± 1.0	30.5 ± 0.5	-0.3 ± 0.6	-1.000	0.423
Width (cm)	10.4 ± 0.3	10.4 ± 0.2	-0.1 ± 0.1	-1.000	0.423
Weight (g)	745.9 ± 27.9	607.9 ± 6.3	-138.0 ± 25.0	-9.563	0.011*

Note. M = mean; SD = standard deviation; MD = mean difference (b-a); *$p < 0.05$; Sig.= significant two-tailed.

As illustrated in Table 4.13, based on the outcomes of their shoe sizes, the participants generally preferred to wear larger shoe sizes than their measured shoe sizes, because of their shoes with wiggle room, a thumb's width of room between the end of their longest toe and the front of their shoe so that they feel like comfortable and enjoyable.

Table 4.13. *Descriptive Statistic of US Shoe Sizes*

Measured Shoe Sizes Mean ± SD	Preferred Shoe Sizes Mean ± SD	Test Shoe Sizes Mean ± SD
9.76 ± 0.5	10.5 ± 0.5	9.74 ± 0.3

Note. SD = standard deviation.

As presented in Table 4.14, the average measured shoe sizes of male participants was US size 9.76; however, the average preferred wearing shoe sizes of participants was US size 10.5. The allocated shoe sizes (US size 9.74) were similar to the average measured shoe sizes. Their preferred shoe sizes indicated significantly mean difference between both measured shoe sizes (MD = -0.69, $p < 0.001$) and test shoe sizes (MD = 0.70, $p < 0.001$). However, no significant difference between the measured and test shoes was found. Au and Goonetilleke (2007) found that there are differences between perceive fit and preferred type of fit, and the comfortable shoes of ladies' dress shoes are related to perceived fit.

Table 4.14. *Comparisons with US Shoe Sizes*

	Paired Sample *t*-Test		
Types of Sizes	MD ± SD	*t*-test	Sig.
Measured shoes – Preferred shoes	-0.69 ± 0.4	-9.735	0.000***
Measured shoes – Test shoes	0.01 ± 0.3	0.274	0.786
Preferred shoes – Test shoes	0.70 ± 0.4	11.215	0.000***

Note. ***$p < 0.001$; Sig.= significant two-tailed.

Correlation coefficient of kinesiology variables. Table 4.15 showed paired sample correlation coefficient between sets of variables was ranged from 0.46 (moderate) to 0.96 (very strong) in different three movements (walking on flat ground, ascending stairs and descending stairs), according to the outcomes of paired sample correlations. It can be explained that each dependent variable (stance time, peak range of motion, ground reaction force, and moment) was not significantly different linear association between sustainable shoes and commercial leather shoes among different movements in general. In other words, it can be assumed by a similar performance between sustainable shoes and commercial leather shoes.

Table 4.15. *Paired Sample Correlation Matrix of Each Dependent Variable*

	ST [b]	P-angle (hip)[b]	P-angle (knee)[b]	P-angle (ankle)[b]	Vertical GRF[b]	Anterior GRF[b]	Posterior GRF[b]	Moment (hip)[b]	Moment (knee)[b]	Moment (ankle)[b]
ST[a]	0.96[c] 0.73[d] 0.82[e]									
P-angle (hip)[a]		0.92[c] 0.90[d] 0.80[e]								
P-angle (knee)[a]			0.46[c] 0.70[d] 0.70[e]							
P-angle (ankle)[a]				0.46[c] 0.70[d] 0.70[e]						
Vertical GRF[b]					0.90[c] 0.77[d] 0.85[e]					
Anterior GRF[b]						0.87[c] 0.77[d] 0.74[e]				
Posterior GRF[b]							0.80[c] 0.54[d] 0.71[e]			
Moment (hip)[a]								0.85[c] 0.87[d] 0.80[e]		
Moment (knee)[a]									0.83[c] 0.80[d] 0.87[e]	
Moment (ankle)[a]										0.60[c] 0.67[d] 0.66[e]

Note. all correlations are significant at the 0.01 level (2-tailed); P-angle = peak angle in range of motion; [a] = leather shoe; [b] = sustainable shoes; [c] = walking on flat ground; [d] = ascending stairs; [e] = descending stairs.

Kinematic Approach

In this study, a sagittal plane (most useful description to biomechanically understand walking patterns) tending to yield the flexion-extension motions, moments along with flexion-extension, and patterns of movement between leather shoes and sustainable shoes at the hip, knee, and ankle was recorded. The analysis of the temporal parameter (stance time) and a peak angle in range of motion (ROM) in the kinematic approach revealed wearers' performance comparing leather shoes with sustainable shoes in normal and stair walking mechanics using a paired simple *t*-test ($p < 0.05$).

Stance Time

As shown in Table 4.16, the results of this study demonstrated that means of stand time was longer when participants were ascending stairs (M_S = 0.90; M_L= 0.91) than walking on flat ground (M_S = 0.69; M_L = 0.68) and descending stairs (M_S = 0.70; M_L = 0.70).

Hypothesis for Stance Time

H1: There are no differences in stance time of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

The mean of stance time on a temporal parameter for the three conditions showed no significant mean differences (MD = M_S - M_L) between the two shoes. Therefore, both shoes were influenced by stance time during three conditions.

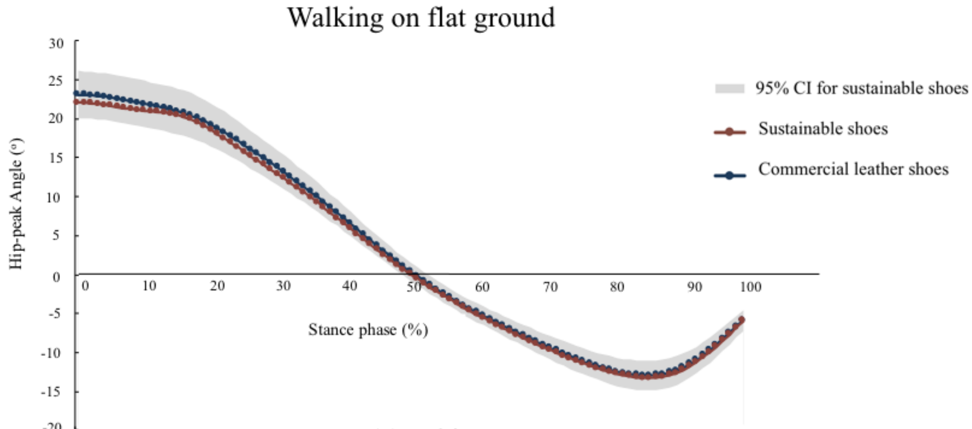
Table 4.16. *Results for Stance Time*

	Leather Shoes[a]	Sustainable Shoes[b]	Paired Sample *t*-Test		
Stance time (s)	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Walking on flat ground	0.68 ± 0.06	0.69 ± 0.06	0.01 ± 0.02	1.671	0.103
Ascending stairs	0.91 ± 0.14	0.90 ± 0.11	-0.01 ± 0.10	-0.474	0.639
Descending stairs	0.70 ± 0.08	0.70 ± 0.09	0.00 ± 0.05	0.113	0.911

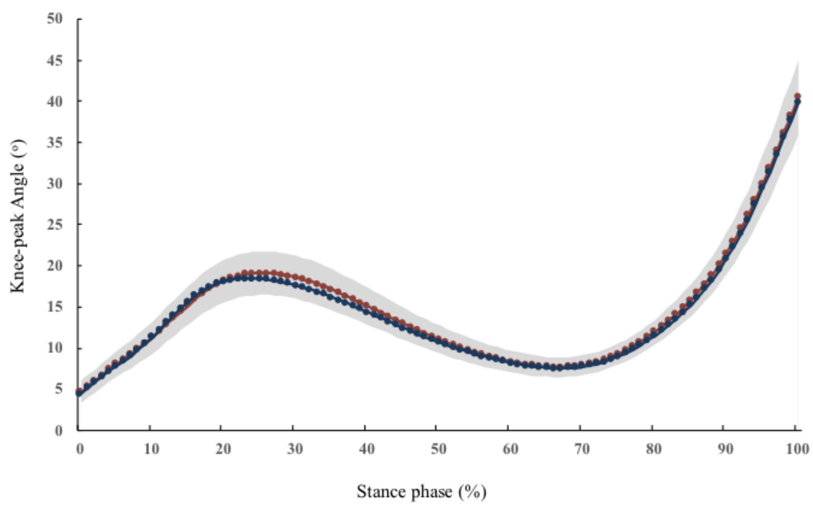
Note. SD = standard deviation; MD = mean difference (b-a); Sig.= significant two-tailed.

Peak Joint Angles in Range of Motion (ROM)

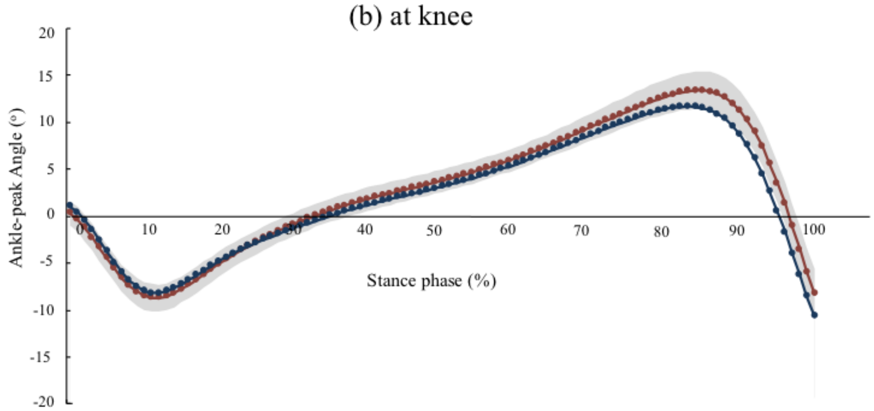
In the sagittal plane, the means of peak angles in range of motion (ROM) at the hip, knee, and ankle throughout gait cycle during participants' walking on flat ground and stair ascent and descent are presented in Figure 4.8 (flat ground), Figure 4.9 (ascending stairs), and Figure 4.10 (descending stairs).



(a) at hip



(b) at knee



(c) at ankle

Figure 4.8. Means of peak angles while walking on flat ground with prototype shoes.

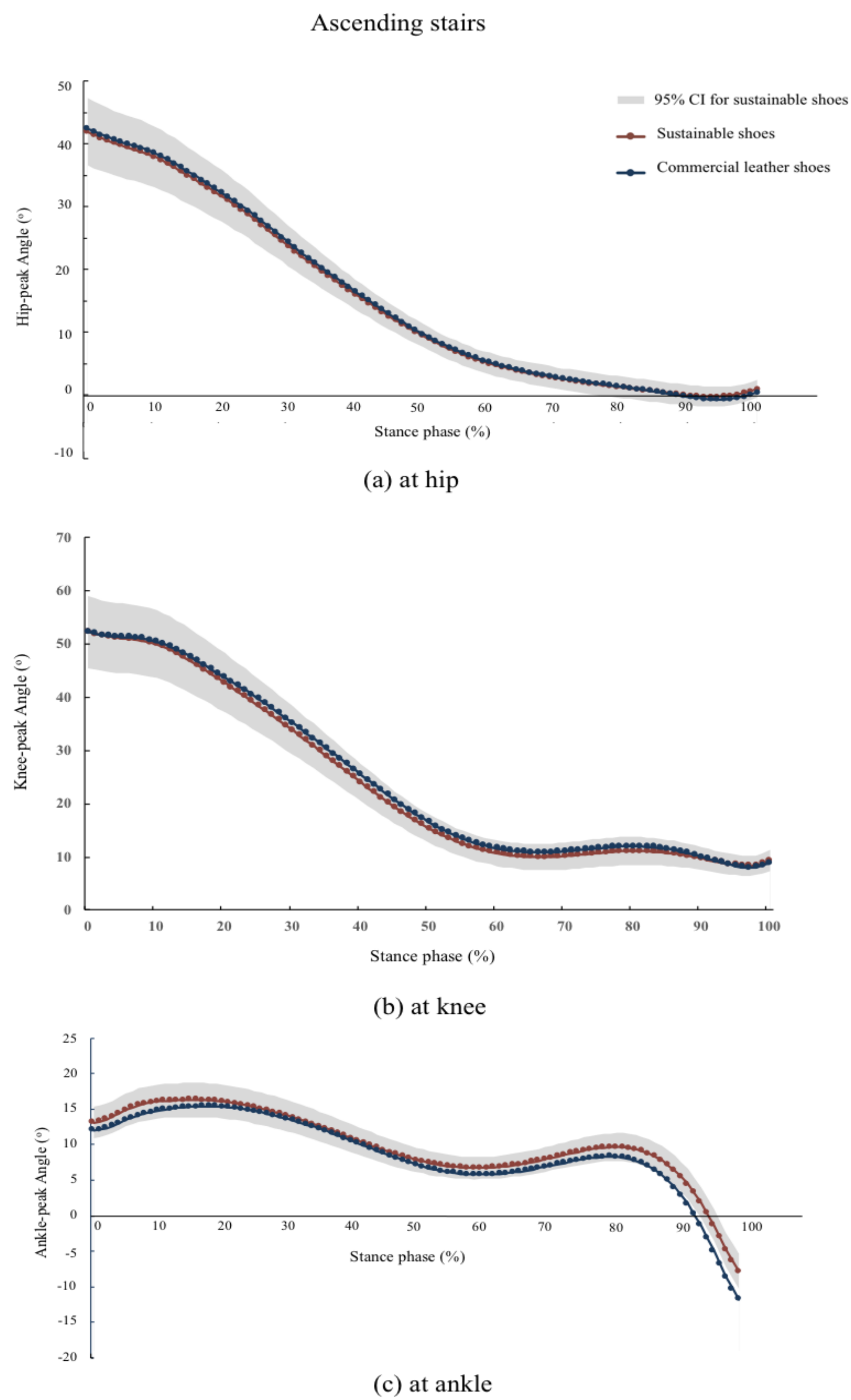


Figure 4.9. Means of peak angles while ascending stairs with prototype shoes.

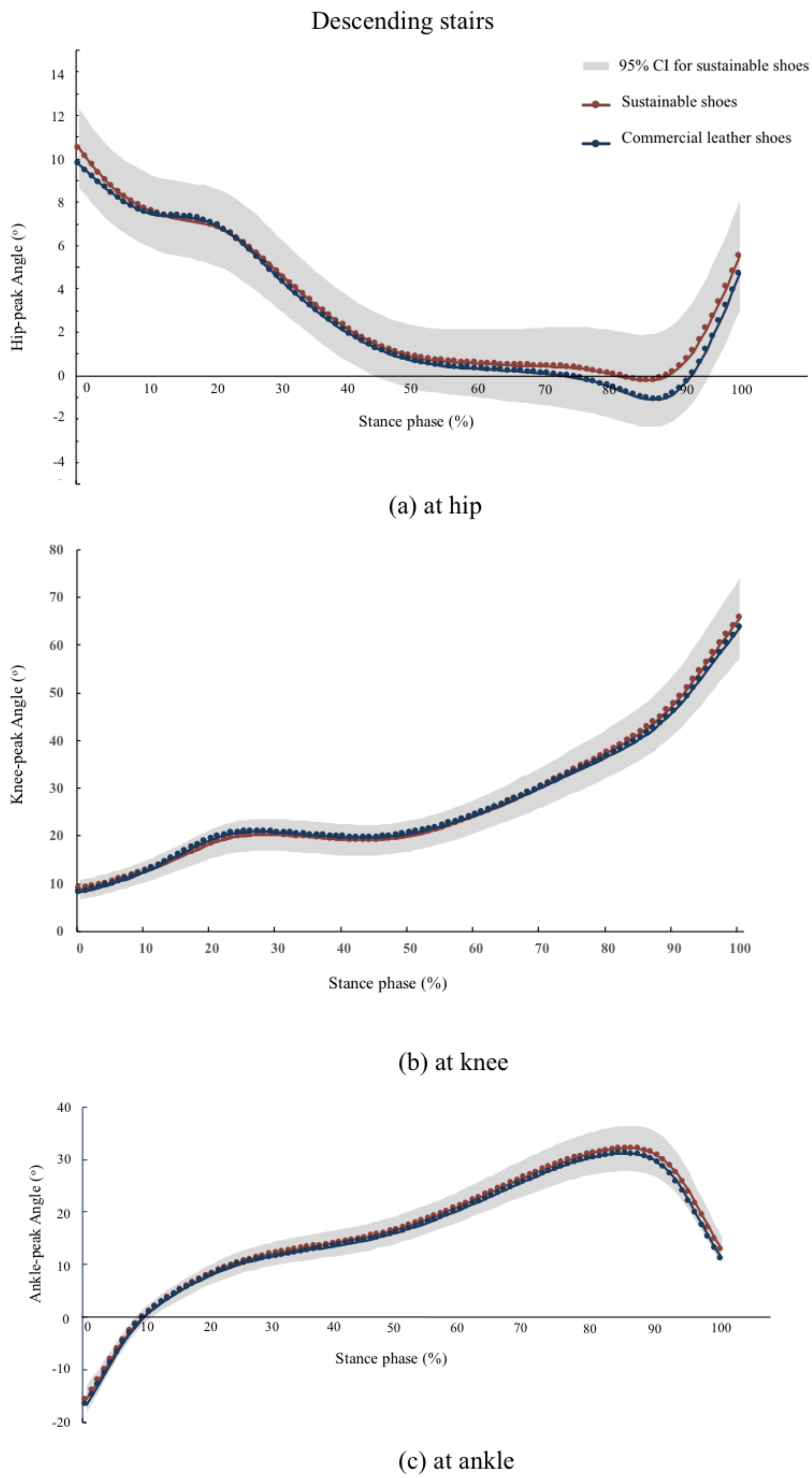


Figure 4.10. Means of peak angles while descending stairs with prototype shoes.

During normal walking, ascending stairs, and descending stairs, the means of ROM for leather shoes were placed at a 95% confidence interval (CI), as indicated by the gray shading in the figures intended to represent sustainable shoes in general, and illustrated the similar patterns for movements at the hip, knee, and ankle. However, the patterns of peak angles at the ankle in the three conditions showed slight differences (between 2-3°) between the two shoes at three quarters of the stance phase. Furthermore, gradual differences emerged in the patterns of peak hip angles in the descending stairs condition between the two shoes at the stance phase (50-100%).

Hypothesis for Peak Joint Angles in Range of Motion

H2: There are no differences in a peak angle in range of motions (hip, knee, and ankle) of gait between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

As shown in Table 4.17, the mean scores of sustainable shoes (M_S) were generally higher than those of the leather shoes (M_L) in each condition, so were then statistically comparable with the leather shoes. Several studies (e.g., Andriacchi et al., 1980; Livingston, Stevenson, & Olney, 1991; Protopapadaki et al., 2007) investigated stair climbing kinetics and kinematics of hip, knee, and ankle joints as subjects ascend and descend stairs. Similar to the findings from these previous studies (Andriacchi et al., 1980; Livingston et al., 1991; Protopapadaki et al., 2007), hip flexion angles during stair ascending were higher than during stair descending; however, knee angles while participants were ascending stairs were less than when participants descended stairs in this study. Ankle angles (plantarflexion-dorsiflexion) while ascending stairs were less than during the descending of stairs. Different subjects' height, the step dimension, marker placements, and motion analysis devices may be factors for the different results among studies and this and prior studies.

Peak hip angles (M_L=25°; M_S=27°) for walking on the flat ground generated lower means than those (M_L=48°; M_S=49°) for when subjects were ascending stairs and yielded higher means than those (M_L=12°; M_S=12°) during the descending of stairs. Meanwhile, peak knee (M_L=16°; M_S=16°) and ankle angles (M_L=14°; M_S=16°) when participants were walking on flat ground produced lower means than those for ascending and descending stairs. Peak knee (M_L=60°; M_S=61°) and ankle angles (M_L=18°; M_S=19°) when ascending stairs showed lower means than peak knee (M_L=74°; M_S=75°) and ankle angles (M_L=37°; M_S=37°) during the descending of stairs. Lower extremity ROM during ascending and descending stairs was significantly increased, compared with normal walking (Alcock, O'Brien, Vanicek, 2014; Sheehan & Gottschall, 2011) in a sagittal plane; however, peak hip and ankle angles in ROM during only walking on flat ground yielded statistically significant mean differences (MD_{hips} = 1.1; MD_{ankles} = 2.0, $p < 0.05$) between the two shoes.

Table 4.17. *Results of Peak Angles in Range of Motion*

	Leather Shoes[a]	Sustainable Shoes[b]	Paired Sample *t*-Test		
	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Walking on flat ground					
Peak hip angle (°)	25.41 ± 4.42	26.46 ± 4.28	1.05 ± 3.12	2.05	0.048*
Peak knee angle (°)	15.62 ± 6.91	16.36 ± 6.72	0.74 ± 2.73	1.647	0.108
Peak ankle angle (°)	13.64 ± 6.33	15.64 ± 4.25	2.00 ± 5.76	2.108	0.042*
Ascending stairs					
Peak hip angle (°)	48.21 ± 4.83	48.58 ± 5.38	0.37 ± 3.25	0.697	0.491
Peak knee angle (°)	60.00 ± 6.32	60.85 ± 6.15	0.85 ± 2.87	1.804	0.080
Peak ankle angle (°)	17.97 ± 7.15	19.24 ± 3.98	1.27 ± 5.25	1.466	0.151
Descending stairs					
Peak hip angle (°)	11.49 ± 3.98	12.19 ± 4.59	0.70 ± 3.66	1.164	0.252
Peak knee angle (°)	73.56 ± 9.56	75.26 ± 8.85	1.70 ± 5.99	1.727	0.093
Peak ankle angle (°)	36.70 ± 8.03	37.41 ± 5.77	0.70 ± 5.81	0.738	0.465

Note. SD = standard deviation; MD = mean difference (b-a); *$p < 0.05$; Sig.= significant two-tailed.

These statistically significant results, which are likely due to differences among weight, thickness, and outsole shape of the two shoes, point to the sustaining of balance and stability while walking on flat ground. No statistically significant differences for peak angles of the hip, knee, and ankle were found between the two shoes while ascending and descending stairs.

Kinetic Approach

The kinetic approach can be validated against external force measurements. It focuses on an inverse dynamics-derived ground reaction forces (GRF) and joint moments from kinematics and body segment parameters.

Ground Reaction Forces (GRF)

Means of peak ground reaction force in vertical and anterior-posterior directions at the hip, knee, and ankle in a sagittal plane during three conditions provided similar patterns for participants who wore both shoes during three conditions. The mean of vertical ground reaction force (vGRF) yielded at both the beginning (20%) and the end (80%) of the stance phase were higher during participants' walking conditions (see Figures 4.11). However, during walking on flat ground the mean of vGRF in stance phase (0-15%) for leather shoes was out of 95% confidence interval (CI), as indicated by the gray shading in the figures intended to represent sustainable shoes. The vGRF yielded at the beginning of the stance phase was less during participants' ascending than their descending stairs, while the vGRF produced at the end of the stance phase was higher during both ascending and descending stairs. These results were consistent with previous findings in terms of ground reaction forces during stair ascent and descent in healthy young men and women (Protopapadaki et al., 2007).

The means of the anterior and posterior ground reaction force (apGRF) yielded at the stance phase illustrated positive and negative values in the three walking conditions. For apGRF, the values pertinent to the leather shoes were higher than those related to the sustainable shoes during each condition (see Figure 4.12). During walking on flat ground the means of apGRF in stance phase (10-12%; 20-25%, respectively) for leather shoes was out of 95% confidence interval (CI), as indicated by the gray shading in the figures intended to represent sustainable shoes.

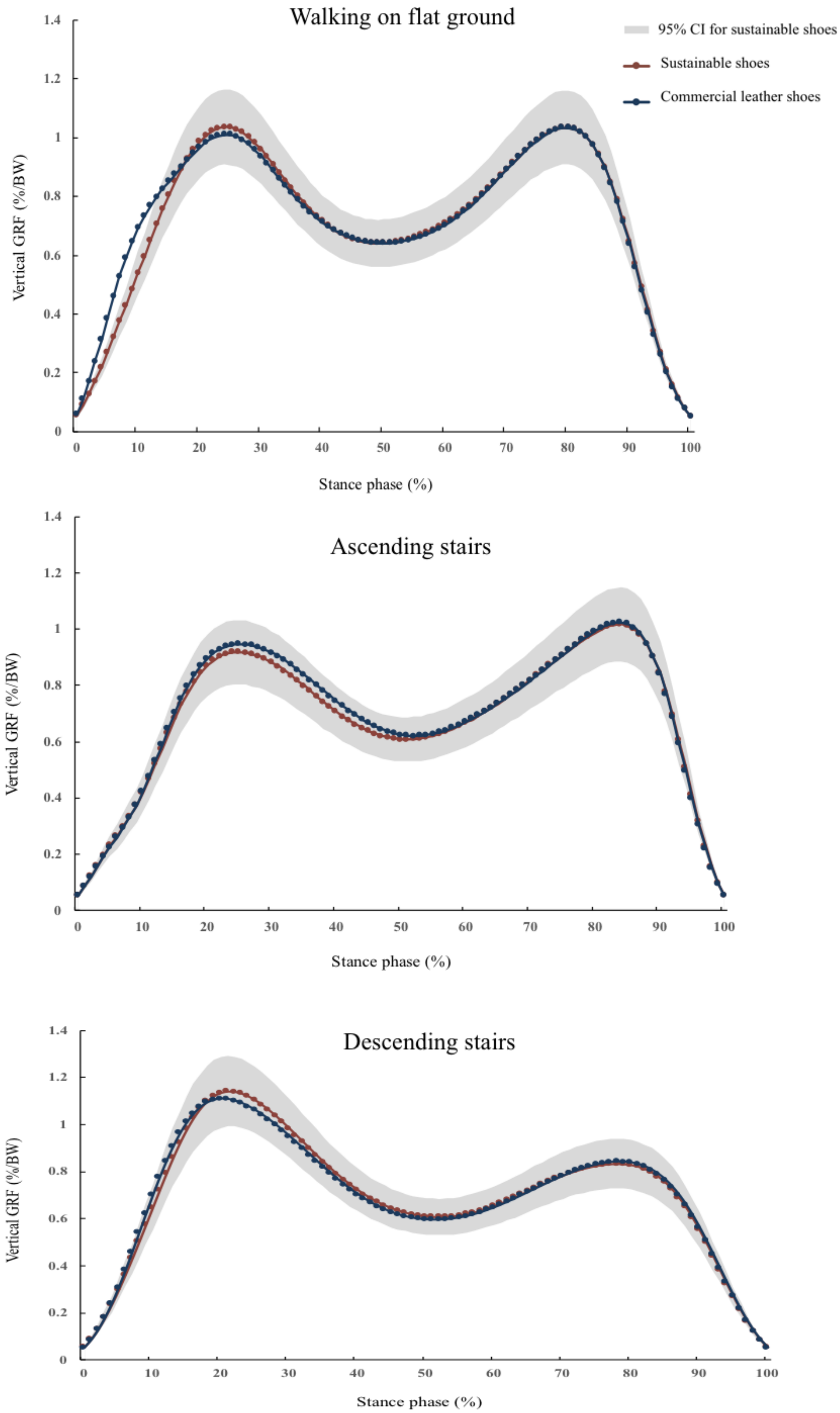


Figure 4.11. Means of vertical GRFs while walking conditions with prototype shoes.

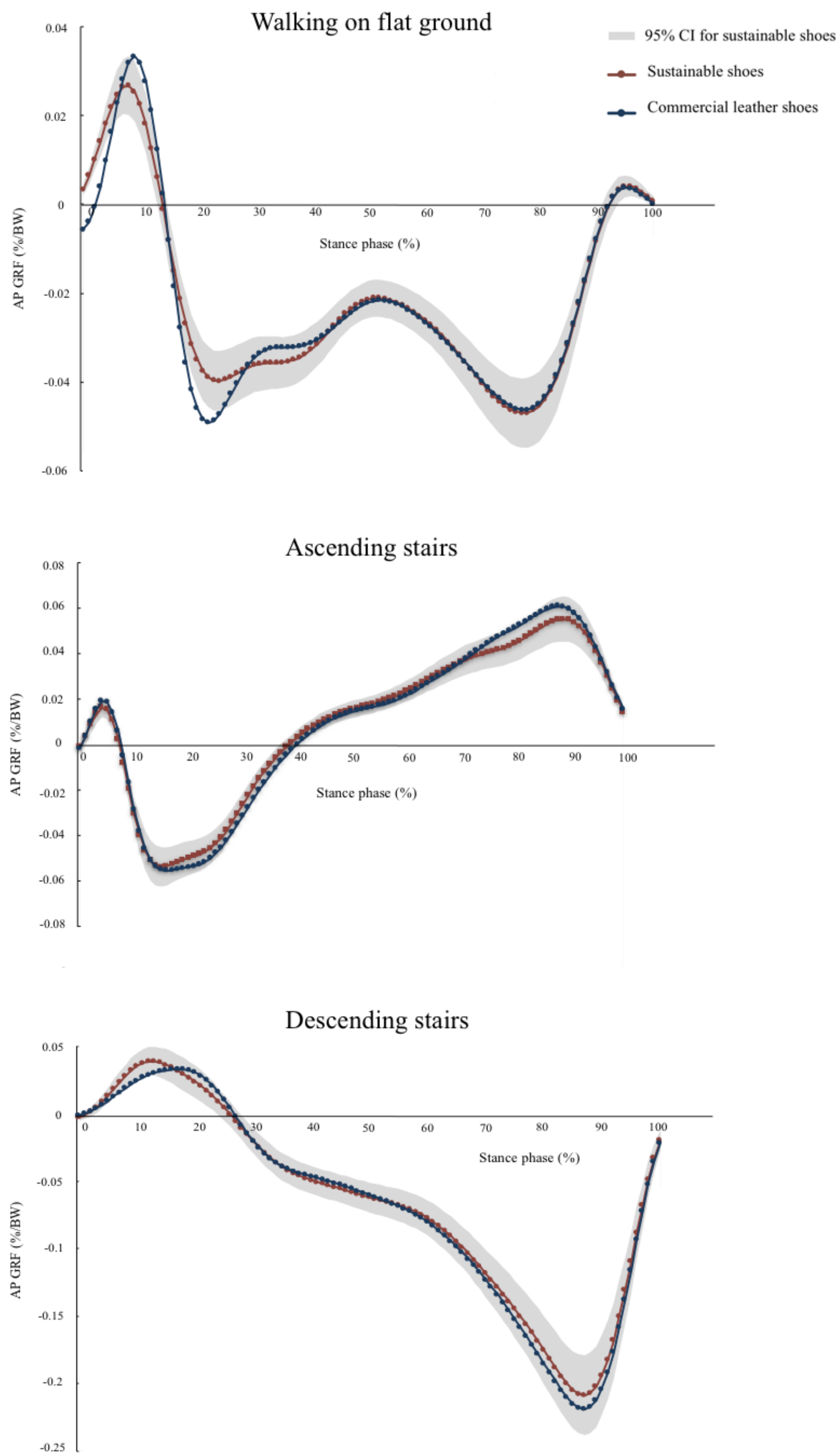


Figure 4.12. Means of AP GRFs while walking conditions with prototype shoes.

Hypothesis for Ground Reaction Forces (GRF)

H3: There are no significant differences in ground reaction forces (hip, knee, and ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

As shown in Table 4.18, the results of the *t*-test showed the peak values of vGRF had a higher mean score for sustainable shoes (M_S) than that of leather shoes (M_L) in general. Statistically significant mean differences ($MD = M_S - M_L$) were found between the leather shoes and sustainable shoes at the peak values of GRF during participants' walking on flat ground ($MD = 0.03$, $p < 0.001$) and ascending stairs ($MD = -0.02$, $p < 0.01$). Similar to our findings, Chiu and Wang (2007) reported that wearing shoes with a rounded shape outsole had positive effects on lowering the vGRF over wearing shoes with flat outsoles during walking on flat ground and ascending stairs in terms of vGRF. In this study, the thick material of the curve-shaped outsole for the leather shoes was polyurethane, while the thin material of the flat shape outsole for sustainable shoes was cork.

For vGRF, however, no statistically significant mean differences between the leather shoes and sustainable shoes during descending stairs were found. Therefore, it can be stated that the shock absorption effectiveness in the outsole of shoes performs similarly for both the shoes during descending stairs and for walking on flat ground and ascending stairs, regardless of the outsole's thickness or material composition. In terms of walking behavior, the entire portion of the outsole makes contact with the surface of the ground during normal walking, while only the toe portion of the outsole is in touch with the ground's surface on a staircase (during ascending and descending stairs).

Statistically significant mean differences (MD) were found between the two shoes at the peak values of anterior ground reaction force (aGRF) during participants' walking on flat ground ($MD = -0.01$, $p < 0.001$). It was also found that there were statistically significant mean differences (MD = M_S - M_L) between the two shoes at the peak values of posterior ground reaction force (pGRF) during walking on flat ground (MD = 0.01, $p < 0.001$) and ascending stairs (MD = 0.01, $p < 0.05$).

Table 4.18. *Results of Vertical, Anterior, and Posterior GRFs*

	Leather shoes[a]	Sustainable shoes[b]	Paired Sample *t*-Test		
	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Walking on flat ground					
Vertical GRF (%BW)	1.16 ± 0.09	1.19 ± 0.09	0.03 ± 0.04	4.541	0.000***
Anterior GRF (%BW)	0.04 ± 0.02	0.03 ± 0.02	-0.01 ± 0.01	-4.354	0.000***
Posterior GRF (%BW)	-0.06 ± 0.01	-0.05 ± 0.01	0.01 ± 0.01	6.004	0.000***
Ascending stairs					
Vertical GRF (%BW)	1.09 ± 0.05	1.08 ± 0.05	-0.02 ± 0.03	-2.921	0.006**
Anterior GRF (%BW)	0.08 ± 0.02	0.08 ± 0.02	0.00 ± 0.01	-1.579	0.123
Posterior GRF (%BW)	-0.07 ± 0.01	-0.07± 0.01	0.00 ± 0.01	0.294	0.770
Descending stairs					
Vertical GRF (%BW)	1.34 ± 0.15	1.37 ± 0.15	0.03 ± 0.09	1.819	0.077
Anterior GRF (%BW)	0.06 ± 0.03	0.06 ± 0.03	0.01 ± 0.02	1.391	0.173
Posterior GRF (%BW)	-0.26 ± 0.04	-0.25 ± 0.05	0.01 ± 0.03	2.317	0.026*

Note. BW = body weight; BH = body height; SD = standard deviation; MD = mean difference (b-a); Sig.= significant two-tailed.

Joint Moments

Means of the sagittal plane moment at the hip, knee, and ankle throughout gait cycle in participants' walking on flat ground, stair ascent, and stair descent are illustrated in Figure 4.13 (flat ground), Figures 4.14 (stair ascent), and Figure 4.15 (stair descent). Participants' age (Novak & Brouwer, 2011), walking speed (Kirtley, Whittle, & Jefferson, 1985; Nilsson & Thorstensson, 1989), and weight groups (Strutzenberger, Richter, Schneider, Mundermann, & Schwameder, 2011) influence sagittal plane joint moments while ascending stairs and descending stairs and generate significant differences among the groups. In this study, however, the patterns of joint moments during each condition were similar for the two shoes in the 95 % confidence interval (CI), as presented by the gray shading in the figures to present sustainable shoes in general.

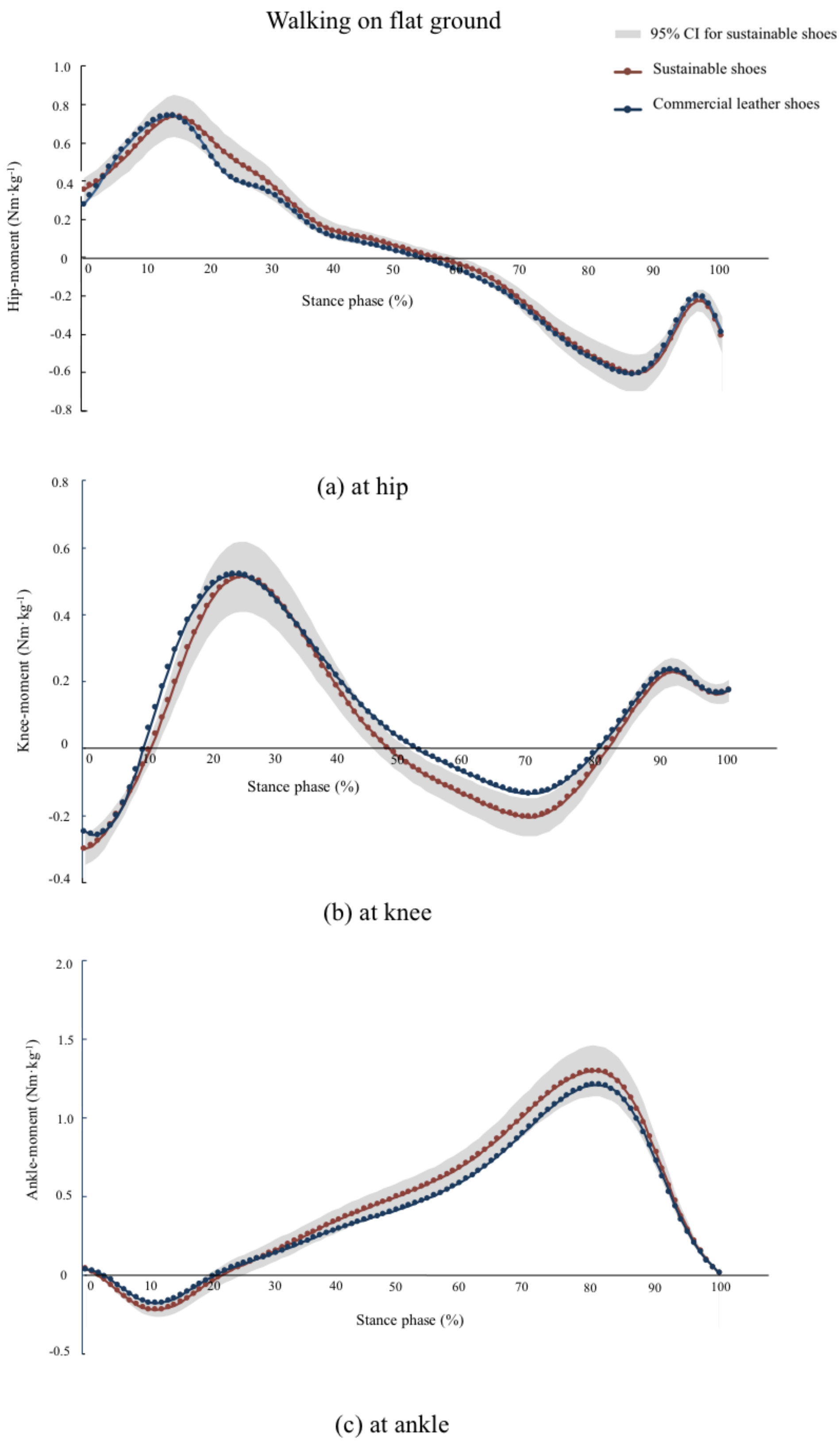
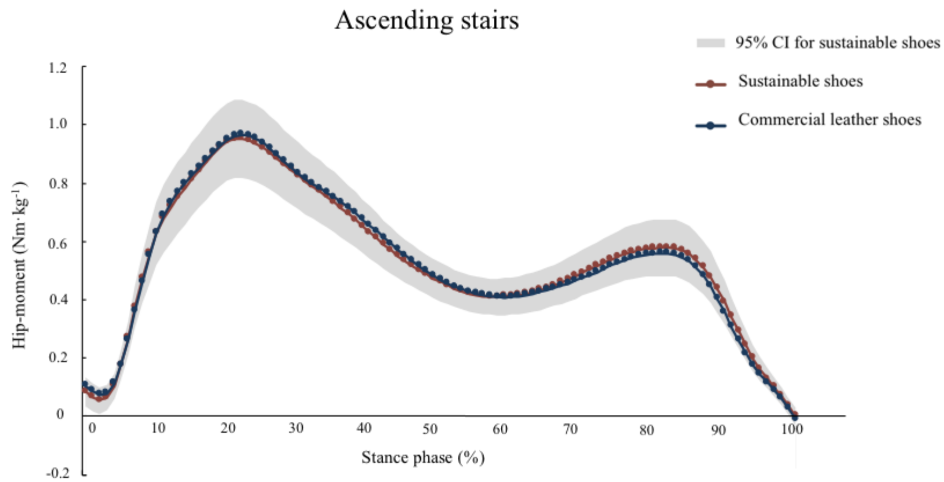
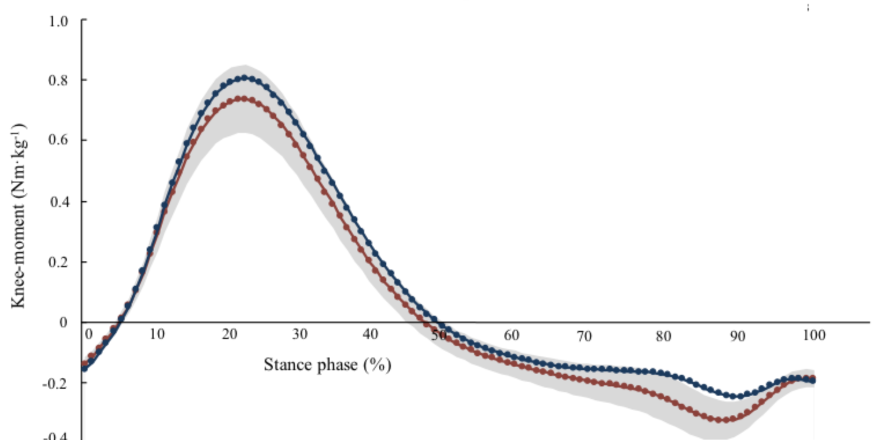


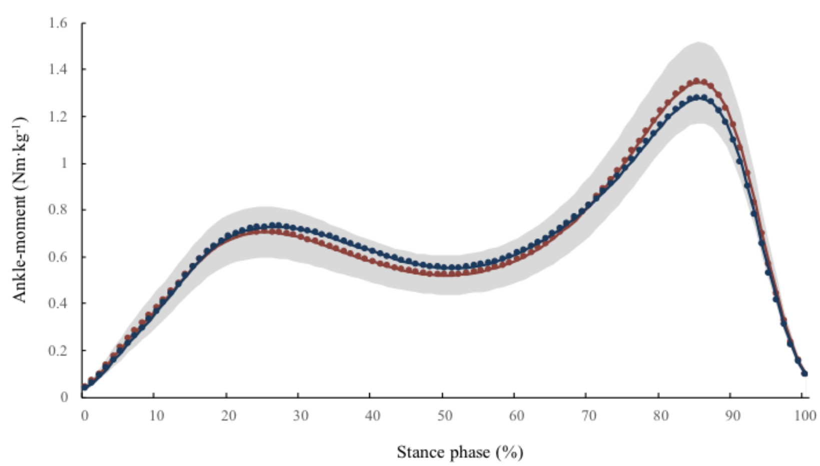
Figure 4.13. Means of moments while walking on flat ground with prototype shoes.



(a) at hip



(b) at knee



(c) at ankle

Figure 4.14. Means of moments while ascending stairs with prototype shoes.

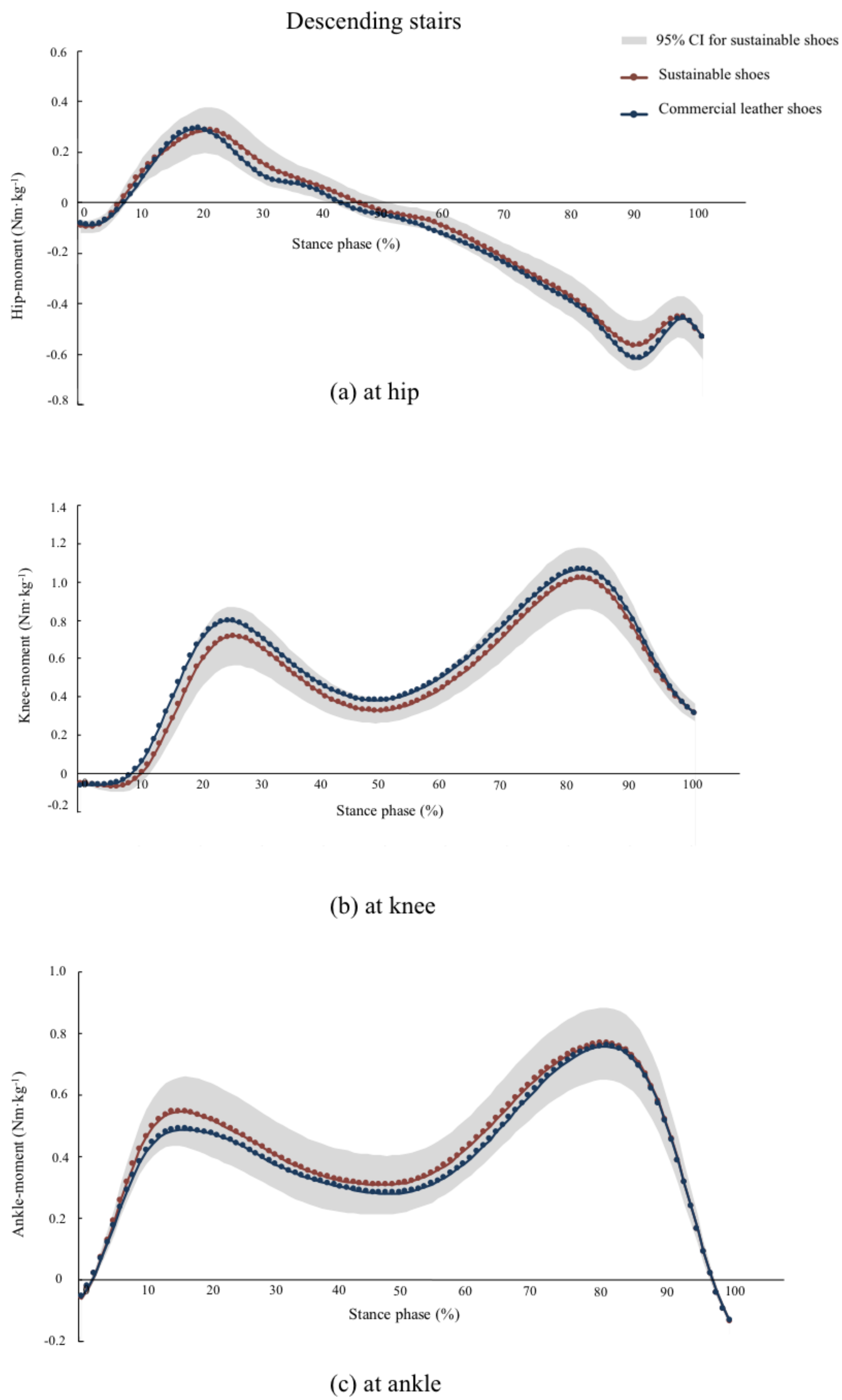


Figure 4.15. Means of moments while descending stairs with prototype shoes.

Hypothesis for Peak Joint Moments

H4: There are no significant differences in joint moments (hip, knee, and ankle) between participants wearing sustainable shoes and commercial leather shoes when: (a) walking on flat ground, (b) ascending stairs, and (c) descending stairs.

As shown in Table 4.19, the ankle moment during participants' walking on flat ground ($MD_{ankles} = 0.07$, $p < 0.01$) and ascending stairs ($MD_{ankles} = 0.1$, $p < 0.001$) showed statistically significant mean differences between the leather shoes and sustainable shoes. Men's dress shoes and sneakers did not significantly affect the normal knee joint torques in terms of the knee, while women's high-heeled dress shoes dramatically yielded knee joint torques in both the sagittal and frontal planes while walking on flat ground (Kerrigan, Karvosky, Lelas, & Riley, 2003; Kerrigan, Lelas, & Karvosky; 2001; Kerrigan, Todd, & Riley, 1998). Similarly, the two shoes did not show differences in knee moments, due to the same stance time or speed during normal walking.

Table 4.19. *Results of Peak Joint Moments*

	Leather shoes[a]	Sustainable shoes[b]	Paired Sample *t*-Test		
	Mean ± SD	Mean ± SD	MD ± SD	*t*-test	Sig.
Walking on flat ground					
Hip moment ($Nm \cdot kg^{-1}$)	0.90 ± 0.22	0.88 ± 0.22	-0.02 ± 0.12	-1.150	0.258
Knee moment ($Nm \cdot kg^{-1}$)	0.62 ± 0.23	0.62 ± 0.26	0.00 ± 0.14	0.042	0.967
Ankle moment ($Nm \cdot kg^{-1}$)	1.41 ± 0.20	1.48 ± 0.14	0.07 ± 0.16	2.762	0.009**
Ascending stairs					
Hip moment ($Nm \cdot kg^{-1}$)	1.18 ± 0.20	1.17 ± 0.21	-0.01 ± 0.10	-0.383	0.704
Knee moment ($Nm \cdot kg^{-1}$)	0.95 ± 0.20	0.89 ± 0.21	-0.07 ± 0.13	-3.080	0.004**
Ankle moment ($Nm \cdot kg^{-1}$)	1.52 ± 0.21	1.62 ± 0.19	0.10 ± 0.16	3.768	0.001***
Descending stairs					
Hip moment ($Nm \cdot kg^{-1}$)	0.45 ± 0.25	0.46 ± 0.26	0.01 ± 0.16	0.377	0.708
Knee moment ($Nm \cdot kg^{-1}$)	1.27 ± 0.30	1.21 ± 0.35	-0.06 ± 0.17	-2.076	0.045*
Ankle moment ($Nm \cdot kg^{-1}$)	1.03 ± 0.15	1.05 ± 0.15	0.02 ± 0.12	1.128	0.267

Note. SD = standard deviation; MD = mean difference (b-a); $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; Sig.= significant two-tailed.

However, the knee moment during stair ascent ($MD_{knees} = 0.07$, $p < 0.01$) and stair descent ($MD_{knees} = -0.06$, $p < 0.05$) showed statistically significant mean differences between the two shoes. Similar to the outcomes reported from previous studies (Andriacchi et al., 1980;

Protopapadaki et al., 2007, Riener, Rabuffetti, & Frigo, 2002), this study found the peak knee flexion moment while ascending stairs was greater than during walking on flat ground; however, the peak hip flexion moment while descending stairs was two times less than while walking on flat ground. In addition, the peak knee moment while walking on flat ground increased during both ascending and descending stairs.

Moreover, the results showed that no statistically significant differences for peak values in the moment for hips and knees, but differences were found between the two shoes during walking on flat ground. No statistically significant differences for peak values in the moment of hips were found between the two shoes during ascending stairs. Finally, no statistically significant differences for peak values in the moment of hips and ankles were found between the two shoes during descending stairs.

Summary of Kinematic and Kinetic Approaches

In Study 4, the hypotheses projected that there were no differences between leather shoes and sustainable shoe prototypes in term of kinematics and kinetics. For kinematics, the stance time in a temporal parameter for the three movements showed no significant mean differences between the mean of the leather shoes and that of the sustainable shoes. No statistically significant differences for peak angles in ROM of hips, knees, and ankles were found between the two shoes during ascending and descending stairs. For kinetics, statistically significant mean differences between the two shoes at peak values of GRF during walking on flat ground were identified. However, no statistically significant mean differences between the two shoes at peak values of anterior and posterior GRF during ascending stairs and in vertical and anterior GRF during descending stairs were identified. In terms of peak moment, no statistically significant differences for peak values of hips and knees were found between the two shoes while participants were walking on flat ground. Furthermore, no statistically significant differences for peak values in the moment of hips were found between the two shoes during stair ascent. Finally, no statistically significant differences for peak values in the moment of hips and ankles were found between the two shoes during stairs ascent. The findings of this study confirm the kinematic and kinetic approaches for men's sustainable shoes made with MCM as a leather alternate.

Study 4: Wear Testing (Wearers' Perceptions and Acceptance)

The objective of Study 4 was to assess wearers' perceptions and acceptance of the eco-friendly shoes, compared with commercial leather shoes via human wear trials, carried out by completing the online survey questionnaire. The survey consisted of seven parts: (a) participants' demographic characteristics and key body measurements, (b) open-ended questions asking participants' thoughts about biodegradable/sustainable shoes and sustainable shoes' benefits, experiences with the shoes, and limitations for reasonable prices for the shoes, (c) participants' functional needs, (d) expressive needs, and (e) aesthetic needs, (f) the physical fit and participants' comfort during the wear trials, and (g) participants' acceptance of the eco-friendly shoes.

Participants

A total of 42 male subjects (height 1.76 ± 0.06m; mass 77.02 ± 11.28 kg) were recruited. Participants' ages ranged from 18 to 43 years with a mean age of 25. Twenty-one participants were Caucasian/European American, followed by Asian (n = 19) and Hispanic American/Latino (n = 2). The sample size (n = 42) reached a 0.89 power level with an effect size (Cohen's d = 0.5) at $p < 0.05$ for post-hoc power analysis using a G-power software, and these statistics can reduce the chance of making a type II error for a paired sample t-test.

Content Analysis

The results of open-ended questions demonstrated that participants connected the word phrase “sustainable shoes” with notions of the environment (i.e., green and eco-friendly; 26%), economic traits, (i.e., expensive; 10%), recycling (i.e., reusable and disposable; 9%), comfort (6%), and durability (i.e., long lasting; 5%). Nearly 11% of the participants held negative perceptions of the sustainable shoes. Results showed that the phrases of environmental (i.e., natural eco-friendly; 35%), functional (i.e., comfortable; 12%), economic (i.e., low cost; 8%), and aesthetic (i.e., design and color; 2%) were articulated by the study participants as benefits to purchasing sustainable shoes. If the male participants purchase a pair of sustainable shoes, they would deeply consider the main features of the eco-friendly shoes such as function, design, and price of the footwear, as well as the shoes’ environmental impact. Moreover, when the participants were asked to relate their response to the four dimensions (functional, expressive, esthetics, and environmental dimensions) of men’s eco-dress shoes, “functional” (i.e., protection and mobility) was the most important feature of the sustainable shoes, followed by “aesthetic” (i.e., color and design), “environmental” (i.e., recycled/reused materials) and “expressive” (i.e., brand name) dimensions. The “environment” and “price” in the FEA dimensions should be additional factors when considering the perceptions of men’s sustainable dress shoes.

In addition, the majority of participants had never owned (or never heard of) men’s dress shoes made with eco-friendly materials, citing the main reason as a lack of information about men’s sustainable dress shoes. They had no chance to encounter these types of shoes on the market or among footwear brands, in spite of the well-known footwear companies’ (e.g., Nike, Adidas, Under Armour, New Balance, Toms, and Puma) continuous efforts to incorporate sustainability practices. Footwear companies producing sustainable shoes need to promote their product development processes and strategies through social media, as male consumers in this study still felt there are very limited sustainable products available, little information as well as high prices in the footwear market.

About 71% of the participants were willing to pay an average of 16% more for sustainable shoes with a higher or similar quality, aesthetics, and comfort (40%) than traditionally manufactured shoes, which are cheaper or close to the general price of leather (29%), and contribute to a positive environmental effect (31%). On the other hand, 29% of the participants were unwilling to purchase sustainable shoes, due to strong brand and design preference and a desire to save money. Finally, the overall frequency counts of words with regard to sustainable shoes in the open-ended answers were conducted to identify the main themes, such as “shoes” followed by “sustainable,” “environment,” and “comfortable,” using a Nvivo software (see Figure 4.16). Consequently, male participants in this study thoroughly consider functional and aesthetic aspects over environmental and expressive features of sustainable shoes, as a whole.

Figure 4.16. Frequency of words used in open-ended question responses.

Functional-Expressive-Aesthetic Needs-Mobility-Acceptance Model

The survey questionnaire investigated a comparison of commercial leather shoes and sustainable shoes within the functional-expressive-aesthetic needs-mobility-acceptance (FEAMA) model. The following hypothesis was proposed and tested:

H5: There are significant mean differences between commercial leather shoes and sustainable shoes in the overall FEAMA model.

Prior to conducting hypotheses testing using a paired simple *t*-test, the assumption of normality was examined using SPSS in order to avoid multicollinearity problems. As shown in Table 4.20, results of the Shapiro-Wilk test indicated that the *p*-value was set at over 0.05, and that there was significant evidence supporting that each variable was normal.

Table 4.20. *Assumption of Normality for FEAMA Dimensions*

Tests of Normality	Shapiro-Wilk		
	Statistic	*df*	Sig.
1. Functional consumer's needs (8 items)			
a. commercial leather shoes	0.957	42	0.115
b. sustainable shoes	0.974	42	0.438
2. Expressive consumer's needs (8 items)			
a. commercial leather shoes	0.963	42	0.196
b. sustainable shoes	0.967	42	0.268
3. Aesthetic consumer's needs (8 items)			
a. commercial leather shoes	0.977	42	0.561
b. sustainable shoes	0.977	42	0.537
4. Mobility (8itmes)			
a. commercial leather shoes	0.966	42	0.243
b. sustainable shoes	0.955	42	0.096
5. Wearers' acceptance (4itmes)			
a. commercial leather shoes	0.949	42	0.059
b. sustainable shoes	0.953	42	0.083

Note. *df* = degree of freedom; Sig.= significant two-tailed.

As shown in Table 4.21, the sum scores (SS) of sustainable shoes were higher than those of leather shoes, and statistically significant mean differences between the two shoes were found for the four dimensions – function (SS_L= 24.8; SSs = 26.7, $p < 0.01$), expression (SS_L = 25.6; SSs = 27.5, $p < 0.05$), aesthetics (SS_L = 23.2; SSs = 25.0, $p < 0.05$), and acceptance (SS_L =12.5; SSs =

15.7, $p < 0.001$). However, only the mobility dimension had higher sum scores (SS) for leather shoes ($SS_L = 28.8$) than that of sustainable shoes ($SS_S = 28.7$), but no statistically significant mean differences between the two shoes were found (see Figure 4.17).

Table 4.21. *Results of Overall FEAMA Dimensions' Analysis*

		Paired Sample *t*-Test		
	Sum (Mean)	MD(SD)	*t*-test	Sig.
1. Functional consumer's Needs (8 items)		1.881 (0.64)	2.962	0.005**
a. commercial leather shoes	24.83 (3.10)			
b. sustainable shoes	26.71 (3.34)			
2. Expressive consumer's Needs (8 items)		1.905 (0.93)	2.045	0.047*
a. commercial leather shoes	25.62 (3.20)			
b. sustainable shoes	27.52 (3.44)			
3. Aesthetic consumer's Needs (8 items)		1.786 (0.81)	2.213	0.033*
a. commercial leather shoes	23.21 (2.90)			
b. sustainable shoes	25.00 (3.13)			
4. Mobility (8itmes)		-0.143 (0.39)	-0.365	0.717
a. commercial leather shoes	28.83 (3.60)			
b. sustainable shoes	28.69 (3.59)			
5. Wearer's acceptance (4itmes)				
a. commercial leather shoes	12.52 (3.13)	3.190 (0.52)	6.170	0.000***
b. sustainable shoes	15.71 (3.93)			

Note. SD = standard deviation; MD = mean difference (b-a); *$p < 0.05$; ** $p < 0.01$; ***$p < 0.001$; Sig. = significant two-tailed.

Each dimension was further analyzed to deepen our understanding of each attribute within the five dimensions.

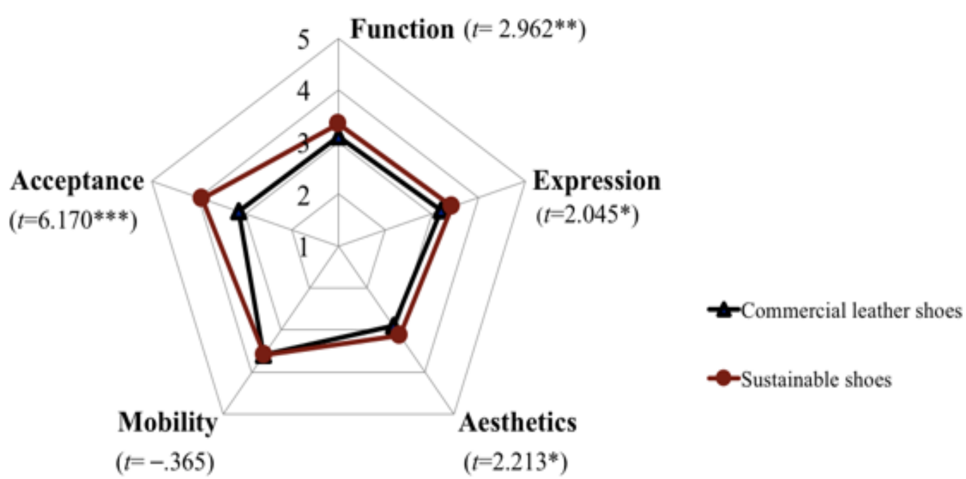


Figure 4.17. Mean differences with five dimensions.

Functional Consumer's Needs

H6: There are significant mean differences between commercial leather shoes and sustainable shoes in terms of functional consumer needs.

As shown in Table 4.22, for the functional dimension, statistically significant mean differences between the sustainable shoes and the leather shoes were found in terms of ventilation ($M_S = 3.38$; $M_L = 2.57$, $p < 0.001$), insulation quality ($M_S = 2.98$; $M_L = 2.57$, $p < 0.05$), and being light weight ($M_S = 3.71$; $M_L = 3.31$, $p < 0.01$). This might be the results of using a lightweight, flexible, and breathable MCM configuration (BC non-woven mat, denim fabric, and hemp fabric) in the sustainable shoes instead of calf-and pig-skin leathers of the leather shoes, according to the MCM's basic properties in Study 2.

Table 4.22. *Results of Functional Consumer's Needs*

		Paired Sample *t*-Test		
	Mean (SD)	MD (SD)	*t*-test	Sig.
1a. The comfort of leather shoes should be improved	3.17 (0.99)	0.33 (1.30)	1.661	0.104
1b. The comfort of sustainable shoes should be improved.	3.50 (0.97)			
2a. The fit of leather shoes should be improved.	3.21 (0.87)	-0.17 (1.45)	-0.747	0.460
2b. The fit of sustainable shoes should be improved.	3.05 (1.04)			
3a. The durability of leather shoes should be improved.	3.02 (0.90)	0.07 (1.33)	0.347	0.730
3b. The durability of sustainable shoes should be improved.	3.10 (0.93)			
4a. The ventilation quality (breathable-air permeability) of leather shoes should be improved.	2.57 (0.70)	0.81 (0.99)	5.280	0.000***
4b. The ventilation quality (breathable-air permeability) of sustainable shoes should be improved.	3.38 (0.83)			
5a. The insulation quality (optimal temperature inside) of leather shoes should be improved.	2.57 (0.83)	0.41 (1.11)	2.373	0.022*
5b. The insulation quality (optimal temperature inside) of sustainable shoes should be improved.	2.98 (0.84)			
6a. The leather shoes should be light weight.	3.31 (0.90)	0.41 (0.94)	2.795	0.008**
6b. The sustainable shoes should be light weight.	3.71 (0.92)			
7a. The leather shoes should be easy to put on and take off.	3.64 (0.96)	0.07 (0.92)	0.503	0.618
7b. The sustainable shoes should be easy to put on and take off.	3.71 (0.84)			
8a. Overall, the functional needs of leather shoes should be improved.	3.33 (0.65)	-0.05 (0.88)	-0.350	0.728
8b. Overall, the functional needs of sustainable shoes should be improved.	3.29 (0.60)			

Note. SD = standard deviation; MD = mean difference (b-a); *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; Sig. = significant two-tailed.

Expressive Consumer's Needs

H7: There are significant mean differences between commercial leather shoes and sustainable shoes in terms of expressive consumer needs.

As illustrated in Table 4.23, for the expressive dimension, the attribute of conveying a leading role showed a statistically significant mean difference between the two shoes ($M_S = 3.67$; $M_L = 2.74$, $p < 0.001$). The participants might perceive themselves as being leaders of environmental awareness to the public when wearing eco-friendly shoes.

Table 4.23. *Results of Expressive Consumer's Needs*

		Paired Sample *t*-Test		
	Mean (SD)	MD (SD)	*t*-test	Sig.
1a. Wearing the leather shoes helps me look better than other men.	3.29 (0.92)	-0.21 (1.32)	-1.055	0.298
1b. Wearing the sustainable shoes helps me look better than other men.	3.07 (0.89)			
2a. The leather shoes should make me look fashionable.	3.45 (0.80)	0.17 (1.03)	1.045	0.302
2b. The sustainable shoes should make me look fashionable.	3.62 (0.80)			
3a. The leather shoes should make me look professional.	3.90 (0.82)	0.00 (1.15)	0.000	1.000
3b. The sustainable shoes should make me look professional.	3.90 (0.73)			
4a. Wearing the leather shoes helps me convey my kind identity as a gentleman.	3.29 (0.89)	0.12 (1.19)	0.646	0.522
4b. Wearing the sustainable shoes helps me convey my kind identity as a gentleman.	3.40 (0.96)			
5a. Wearing the leather shoes helps me feel more masculine.	2.95 (1.04)	0.00 (0.94)	0.000	1.000
5b. Wearing the sustainable shoes helps me feel more masculine.	2.95 (0.80)			
6a. Wearing the leather shoes helps with my self-image as a mature young adult.	3.26 (1.01)	0.24 (1.32)	1.167	0.250
6b. Wearing the sustainable shoes helps with my self-image as a mature young adult.	3.50 (0.80)			
7a. I am willing to play an important role of conveying the importance of wearing the leather shoes to other men.	2.74 (0.80)	0.93 (1.24)	4.863	0.000***
7b. I am willing to play an important role of conveying the importance of wearing the sustainable shoes to other men.	3.67 (1.03)			
8a. Overall, the expressive needs of the leather shoes should be improved.	2.74 (0.80)	0.67 (0.93)	4.654	0.000***
8b. Overall, the expressive needs of the sustainable shoes should be improved.	3.40 (0.92)			

Note. SD = standard deviation; MD = mean difference (b-a); ***$p < 0.001$; Sig.= significant two-tailed.

Consequently, it is important for wearers to express symbolic messages of success or attractiveness with the products (e.g., snowboard helmet; Chea & Schofield-Tomschin, 2010; coat and shoes; Cao et al., 2014b).

Aesthetic Consumer's Needs

H8: There are significant mean differences between commercial leather shoes and sustainable shoes in terms of consumers' aesthetic needs.

As illustrated in Table 4.24, for the aesthetic dimension, the attribute of texture yielded statistically significant mean differences between the two shoes ($M_S = 3.21$; $M_L = 2.69$, $p < 0.05$). The eco-layer material configuration used in the sustainable shoes might allow wearers to be more comfortable than when they wore the leather shoes.

Table 4.24. *Results of Aesthetic Consumer's Needs*

		Paired Sample *t*-Test		
	Mean (SD)	MD (SD)	*t*-test	Sig.
1a. The color of leather shoes should be improved.	2.55 (1.06)	0.31 (1.32)	1.525	0.135
1b. The color of sustainable shoes should be improved.	2.86 (1.12)			
2a. The style of leather shoes should be improved.	3.33 (1.07)	0.00 (1.31)	0.000	1.000
2b. The style of sustainable shoes should be improved.	3.33 (1.12)			
3a. The texture of leather shoes should be improved.	2.69 (1.00)	0.52 (1.44)	2.368	0.023*
3b. The texture of sustainable shoes should be improved.	3.21 (1.09)			
4a. The uniqueness of leather shoes should be improved.	2.86 (0.90)	0.31 (1.20)	1.766	0.102
4b. The uniqueness of sustainable shoes should be improved.	3.17 (0.90)			
5a. An unique design feature of leather shoes should be added.	3.02 (1.12)	0.24 (0.91)	1.705	0.096
5b. An unique design feature of sustainable shoes should be added.	3.26 (1.04)			
6a. The sleek design of leather shoes should be improved.	2.88 (1.02)	0.36 (1.21)	1.921	0.062
6b. The sleek design of sustainable shoes should be improved.	3.24 (1.08)			
7a. The masculine design of leather shoes should be improved.	2.74 (0.89)	0.07(1.05)	0.464	0.660
7b. The masculine design of sustainable shoes should be improved.	2.81 (0.94)			
8a. Overall, the aesthetic needs of leather shoes should be improved.	3.14 (0.98)	-0.02 (1.28)	-0.124	0.904
8b. Overall, the aesthetic needs of sustainable shoes should be improved.	3.12 (1.09)			

Note. SD = standard deviation; MD = mean difference (b-a); *$p < 0.05$; Sig. = significant two-tailed.

Au and Goonetilleke (2007) found that materials stimulate a participant's perception related to the overall fit of shoes; however, aesthetic attributes of ladies' dress shoes have no effect on the comfort or discomfort of shoes. The color of the upper shell made of MCM was dark brown color, which was dyed with used coffee grounds. Therefore, the BC non-woven mats can be produced in different color from natural dye (e.g., onion, grape, and banana skins) or pigments in MCM products.

Mobility Related to Physical Fit and Comfort

H9: There are significant mean differences between commercial leather shoes and sustainable shoes in terms of mobility in three different movement conditions.

As shown in Table 4.25, there are no differences between the two shoes in terms of fit and comfort. Similarly, Cao et al. (2014b) identified fit and comfort (e.g., upper materials and soles) of their shoes made with eco-leather during sitting and walking as evaluated by college students. Outsole materials (i.e., thermosetting resin and chicken feather quilted with a cotton fabric) of their shoes also made participants feel comfortable and hold positive perceptions of the footwear (Cao et al., 2014b). It is important for shoe makers to select suitable materials and shape of outsoles for wearers to make feel comfortable.

Table 4.25. *Results of Mobility on Different Movements*

		Paired Sample *t*-Test		
	Mean (SD)	MD (SD)	*t*-test	Sig.
Walking on flat ground				
1a. How well do the leather shoes fit?	3.62 (0.54)	0.024 (0.68)	0.227	0.822
1b How well do the sustainable shoes fit?	3.64 (0.79)			
2a. How comfortable are the leather shoes?	3.48 (0.74)	0.024 (0.72)	0.216	0.830
2b. How comfortable are the sustainable shoes?	3.50 (0.86)			
Ascending stairs				
3a. How well do the leather shoes fit?	3.93 (0.75)	-0.333 (0.61)	-3.532	0.001***
3b. How well do the sustainable shoes fit?	3.60 (0.70)			
4a. How comfortable are the leather shoes?	3.45 (0.74)	0.190 (0.74)	1.667	0.103
4b. How comfortable are the sustainable shoes	3.64 (0.85)			
Descending stairs				
5a. How well do the leather shoes fit?	3.74 (0.83)	-0.286 (0.74)	-2.496	0.017*
5b. How well do the sustainable shoes fit?	3.45 (0.83)			
6a. How comfortable are the leather shoes?	3.50 (0.80)	0.071 (0.60)	0.771	0.445
6b. How comfortable are the sustainable shoes?	3.57 (0.74)			
Overall movement				
7a. How well do the leather shoes fit?	3.55 (0.67)	0.071 (0.60)	0.771	0.445
7b. How well do the sustainable shoes fit?	3.62 (0.76)			
8a. How comfortable are the leather shoes?	3.57 (0.63)	0.095 (0.53)	1.159	0.253
8b. How comfortable are the sustainable shoes?	3.67 (0.75)			

Note. SD = standard deviation; MD = mean difference (b-a); $*p < 0.05$; $***p < 0.001$; Sig.= significant two-tailed.

However, significantly negative mean differences (M_S - M_L) were found between the leather shoes (M_L) and sustainable shoes (M_S) in terms of fit during ascending (M_S = 3.60; M_L = 3.93; MD = -0.33, $p < 0.001$) and descending stairs (M_S = 3.45; M_L = 3.74; MD = -0.29, $p < 0.05$). This is because eco-materials and cork materials make wearers not feel tight and had their feet feel cushioned during movement, as opposed to leather shoes' tight and restricting qualities. Future studies may be needed to investigate fit and comfort in the different regions of the foot (e.g., toe, arch, and rear-foot) in men's sustainable shoes and to improve outsole materials.

Wearers' Acceptance

H10: There are significant mean differences between commercial leather shoes and sustainable shoes in wearers' acceptance of the shoes.

As illustrated in Table 4.26, the wearers' acceptance dimension showed statistically significant mean differences between the two shoes ($p < 0.001$) in terms of possibility for materials (M_S = 4.21; M_L = 3.63), recommendation (M_S = 3.90; M_L = 3.07), purchase intension (M_S = 4.07; M_L = 3.21), and spending more money (M_S = 3.52; M_L = 2.62). If functional, expressive, aesthetic, and mobility needs were satisfied, participants were willing to buy sustainable shoes instead of leather shoes.

Table 4.26. *Results of Wearers' Acceptance*

		Paired Sample *t*-Test		
	Mean (SD)	MD (SD)	*t*-test	Sig.
1a. It is possible that I will buy the leather shoes with eco-friendly materials.	3.63 (0.73)	0.60 (0.91)	4.229	0.000***
1b. It is possible that I will buy the sustainable shoes with eco-friendly materials.	4.21 (0.61)			
2a. I recommend that friends or families buy the leather shoes.	3.07 (0.75)	0.83 (1.01)	5.347	0.000***
2b. I recommend that friends or families buy the sustainable shoes.	3.90 (0.69)			
3a. I will consider purchasing the leather shoes.	3.21 (0.95)	0.86 (1.18)	4.705	0.000***
3b. I will consider purchasing the sustainable shoes.	4.07 (0.64)			
4a. I am willing to pay more money for the leather shoes.	2.62 (0.85)	0.91 (1.10)	5.330	0.000***
4b. I am willing to pay more money for the sustainable shoes.	3.52 (0.71)			

Note. SD = standard deviation; MD = mean difference (b-a); ***$p < 0.001$, Sig.= significant two-tailed.

Cao et al. (2014b) also indicated that sustainable products made with renewable bio-based and eco-friendly materials could meet consumer's need by improving the design and style of the products. Therefore, the MCM showed the potential to be wearable, mobile, and versatile in various industries.

Summary of Wearers' Perceptions and Acceptance

In Study 4, the hypotheses were to examine whether there were significant mean differences between the sustainable shoes and leather shoes according to participants' perceptions and acceptance of the footwear in the following five dimensions: function, expression, aesthetics, mobility related with physical fit and comfort during wear trials in varied conditions, and wearers' acceptance of shoes. For the four dimensions (function, expression, aesthetics, and acceptance), the mean scores of sustainable shoes were higher than those of the leather shoes and statistically significant mean differences between the two shoes were found. The findings demonstrated that the men's shoes made with the multi-layered material configuration (MCM), which can be a leather substitute, have the potential to attract young male consumers in the future. The participants' perceptions and acceptance of the sustainable shoes made with MCM were significantly higher than those leather shoes commercially available in the market. A majority of male participants also preferred the feel of having their feet touch the ground when walking in the sustainable shoes, a feature made possible, due to the thin outsole of the shoes. Although the participants were very interested in the sustainable shoes made with the MCM configuration, this shoes still promoted a lack of mobility related to the wearers' fit and comfort. However, based on the findings from the material evaluation (Study 2), the shoe prototypes (Study 3) made of MCM still has the potential to be wearable and mobile in footwear industries kinetic and kinematic approaches for wear testing (Study 4), and wearers' perception and acceptance of men's sustainable shoes (Study 4).

CHAPTER 5. SUMMARY AND CONCLUSIONS

This chapter summarizes the research conducted for this study and discusses conclusion and implications of the findings according to the five objectives of this study for both industry and academia. It also discusses the study limitations, identifies areas of future research direction and ends with brief concluding comments.

This research significantly contributes to the understanding a potential a multi-layered cellulosic material (MCM) with material testing and sustainable footwear design and development. The overall purpose of this study was to investigate the compatibility of men' sustainable shoes made with bacterial cellulose (BC) non-woven mats and other eco-friendly materials (i.e., denim fabric, hemp fabric, compressed paper, and cork material), compare the durability and comfort in the performance of newly developed sustainable shoes with those in commercially available leather shoes via human trials, and investigate wearers' perceptions and acceptance of the sustainable shoes. The specific research objectives of each study were as follows:

Study 1 (Objectives 1): To identify important design criteria for sustainable shoes under the cradle-to-cradle design framework by incorporating the 12 principles of green engineering and wearers' functional-expressive-aesthetic needs; and to develop the ISACT for sustainable footwear design process within the integrated theoretical design framework.

Study 2 (Objective 2): To examine the properties of single-layered materials (BC non-woven mat, denim fabric, hemp fabric, calf-skin leather, and pig-skin leather) and multi-layered materials (MCM and MCPL), which determined the compatibility of BC material as a leather alternate.

Study 3 (Objectives 3): To create sustainable shoe prototypes made of MCM and the other eco-friendly materials according to the IsAcT design process for sustainable footwear.

Study 4 (Objective 4 and 5): To evaluate wearers' objective performances in both sustainable shoes and leather shoes using quantitative kinematic and kinetic parameters of lower body movements and to investigate wearers' perceptions and acceptance of the shoes via human wear trials, followed by completion of an online survey questionnaire.

Study 1: Theoretical Model for Sustainable Footwear

In Study 1, the proposed theoretical framework, integrating the FEA consumer's needs model with five principles (1, 2, 7, 10, and 11) of C2C design process model, is a feasible design framework for the sustainable footwear design and development process. Consequently, the framework enables designers and manufacturers to understand the target consumers' needs, to enhance awareness of environmental issues, and to urge them to easily and fully implement sustainability practices into new sustainable product design and development processes. The proposed integrated conceptual framework focuses on the following three stages of the IsAcT design process to: (a) Identify problems and select eco-material, (b) Assess eco-materials and create a prototype, and (c) Test human trial and wearer' perceptions for sustainable footwear. To achieve Objectives 1 and 2, based on the literature reviews, the eco-friendly materials (bacterial cellulosic non-woven mat, denim fabric, and hemp fabric) were selected as a leather alternative for men's sustainable shoes in the footwear industry. The results of Study 1 led Study 2, aiming to investigate basic properties, heat and moisture transfer, and mechanical properties of the eco-friendly materials, comparing these features with leathers.

Study 2: Material Evaluation for Sustainable Shoes

In the footwear industry, the selection of materials is a vital and initial step for ensuring sustainability practices. When considering the design and development of sustainable footwear, leather can be substituted for another biodegradable, renewable material, for example, the cellulosic fiber mat examined in this study. A single layer of cellulosic fiber mat might not be effective for use as a leather alternative in the footwear industry. Therefore, the purpose of our study was to develop MCM and examine its properties – thickness, weight, air permeability, thermal comfort, tensile strength, and wettability – compared with those of MCPL and using an experimental research design. According to the hypotheses, MCM and MCPL were projected to have similar properties. The findings demonstrated that basic properties (thickness, weight, air permeability), heat and moisture transfer properties (evaporative resistance, total heat loss, permeability index, evaporative potential), and mechanical properties (break force) of MCM were better than or similar to those of MCPL, which yields possibilities for using MCM as a leather alternative material.

Statistically significant mean differences in air permeability were found between MCM and MCPL. MCM can be potentially used as the entire shell for sustainable shoes instead of calf- and pig-skin leathers, due to its lightness and air flow capability. MCM had a higher R_{ct} and a lower R_{et} than MCPL. MCM had slightly lower total heat loss than that of MCPL; however, no statistically significant differences were identified between the two materials. MCM had a bit higher permeability index than that of MCPL, indicating that MCM is somewhat more water vapor-permeable than MCPL. Footwear designers and developers may need to consider this fact and use MCM that provides a similar or better thermal comfort than calf- and pig-skin leathers when designing and developing shoes.

Moreover, MCM provides benefits to the wearer's comfort and performance rather than MCPL, as found by examining the EP value of both materials. This finding is meaningful, considering the importance of understanding the evaporative potential of materials for sustainable footwear design and development. MCPL yielded the higher values in break force and elongation over those of MCM, but no statistically significant differences were found between the two materials. The cellulosic fiber mat bonded with denim and hemp, here called MCM, offered improved reinforcing effects and appreciable break force, even when MCM's thickness was increased; the materials were, however, still lightweight. Although MCM showed unstable mechanical properties in terms of elongation and wettability, the quantified break force of MCM was similar to that of MCPL. Further research needs to be conducted to provide more profound arguments regarding this result and suggestions for using MCM as a leather alternative material in terms of these unstable mechanical properties.

This experimental study presented the great potential of MCM to be used as a leather alternative when developing wearable products (e.g., footwear, backpack, and jacket), due to its properties in maintaining a thermal equilibrium in wearers' feet in comparison to MCPL. The results also provided a better understanding of the influence of MCM on the wearers' thermal comfort and the shoes' durability. Consequently, Study 2 in the IsAcT design process for sustainable footwear was unique in its selection of a sustainable design strategy and materials that utilize adaptive MCM to evaluate its properties (physical, heat and moisture transfer, and mechanical properties) for appropriateness as a leather alternative material in the footwear industry. The design and testing procedures for MCM can be useful for other researchers and manufacturers who are willing to develop and test emerging sustainable materials for their use in wearable products' design and development.

Study 3: Sustainable Shoe Prototypes

Sustainable shoe prototypes with three different US men's sizes (i.e., 9.5, 10, and 10.5) created in distinct patterns were made with the MCM in the outer, mid, and inner shells as well as the other materials (compressed paper and cork material) in the midsole and outsole, respectively, following Stages 1 and 2 in the IsAcT design process for sustainable footwear. After developing the men's shoe prototypes using MCM, the sustainable shoes were compared with commercial leather shoes in human performance trials using kinematic and kinetic approaches and wearers' perceptions and acceptance for sustainable shoes.

Study 4: Wear Testing for Sustainable Shoes

Kinematic and Kinetic Approaches

Footwear design and development can either help or hinder foot health. Not only do footwear designers consider promoting healthy and functional feet, but they also aim to fulfill consumer demands for various styles of shoes. For the shoe makers, it is also important to engage in intentional design practices and choose suitable sustainable materials for shoe making if considering environmental sustainability beyond wearers' fit and comfort. Functional footwear is generally designed to be comfortable and stable for body posture and gait to facilitate easy walking and foot protection. Although biomechanics studies have been performed to investigate the effects of footwear (e.g., insoles, outsoles, and heels) during walking using a kinematic and kinetic approach, rarely do shoe designers and researchers investigate wearers' performance comparing a sustainable shoe prototype with commercially available shoes using human wear trials. Therefore, the purpose of this study was to evaluate wearers' performance in men's leather shoes compared to sustainable shoes using an experimental research design. The hypotheses predicted no differences in kinetic and kinematic parameters of gait within participants' lower extremity when wearing the two different shoes while performing the following three conditions.

Great potential for multi-layered cellulosic materials (MCM), consisting of the cellulosic fiber mat, hemp, and denim, selected in Study 1 as a leather alternative, was selected for material evaluation in Study 2. Based on the previous material configuration and evaluation, the sustainable shoe prototype created using unique patterns was made with the MCM for the outer, mid, inner shells and other materials for midsole (compressed papers) and outsole (cork materials). The leather shoes were made by professional shoe makers in a small company using identical patterns of the sustainable shoe prototype. A total of 37 healthy male subjects were obtained for participation in the study. The participants' ages ranged from 18 to 43 years with a mean age of 28.

In terms of kinematics, the results demonstrated that stance time for the three conditions showed no significant mean difference between the two shoes. Peak angles in the range of motion (ROM) of hips and ankles yielded statistically significant mean differences between the two shoes only during walking on flat ground. For ROM, the weight of the shoes could affect hips and ankles rather than knees in the lower extremity during walking on flat ground. However, no statistically significant differences for peak angles of hips, knees, and ankles were found between the two shoes during ascent and descent of stairs.

In terms of kinetics, the mean of vertical ground reaction force (GRF) yielded at the beginning (20%) of the stance phase was higher during participants' stair descent than for other conditions. The results of a *t*-test showed values of GRF produced a higher mean score for sustainable shoes than that of leather shoes in general. Statistically significant mean differences between the two shoes at the peak values of GRF during participants' walking on flat ground and ascending stairs were found. In this study, the thick material of the curve-shaped outsole for the leather shoes was polyurethane, while the thin material of the flat-shaped outsole for the sustainable shoes was cork. For GRF, however, no statistically significant mean differences between the two shoes while participants descended stairs were found. Therefore, it can be stated that the shock absorption effectiveness in the outsole of shoes can be similarly performed for both shoes during descending stairs than for walking on flat ground and ascending stairs, regardless of the outsole's thickness and material composition. In terms of peak joint moments, also, no statistically significant differences for peak values in moment of hips were found between the two shoes during ascending stairs. Finally, no statistically significant differences for peak values in moment of hips and ankles were found between the two shoes during descending stairs.

This experimental study presented the possibilities for the kinematics and kinetics of men's sustainable dress shoes made with MCM as a leather alternative, due to similar performance in wearers' lower extremities in different conditions compared to the leather shoes. The results also provided a better understanding of the influence of materials of a sustainable shoe prototype on wearers' lower extremities.

Wearers' Perceptions and Acceptance

In Study 4, wearers' perceptions and acceptance of the sustainable shoes, compared with commercial leather shoes, were investigated via human trials using survey questionnaire. A total of 42 male subjects were recruited. The participants' ages ranged from 18 to 43 years with a mean age of 25.

Among the five dimensions, only the mobility dimension had a higher mean score for leather shoes than that of sustainable shoes, while no statistically significant mean differences between the two shoes were found. For the remaining dimensions, function, expression, aesthetics, and acceptance, the mean scores of sustainable shoes were higher than those of leather shoes, and statistically significant mean differences between the two shoes were found in these four dimensions. Each dimension was further analyzed to deepen our understanding of each attribute within the five dimensions.

For the functional dimension, statistically significant mean differences between the sustainable shoes and the leather shoes were found in terms of ventilation, insulation quality, and being light weight. This might be the result of using the lightweight, flexible, and breathable materials in sustainable shoes than the characteristics of the materials in the leather shoes. For the expressive dimension, the attribute of conveying a leading role showed a statistically significant mean difference between the two shoes; by wearing eco-friendly shoes, the participants might perceive themselves as leaders in promoting environmental awareness to the public. For the aesthetic dimension, the attribute of texture yielded statistically significant mean differences between the two shoes; the eco-layer material configuration used in the sustainable shoes might allow wearers to be more comfortable than when wearing the leather shoes.

Finally, the wearers' acceptance dimension showed statistically significant mean differences between the two shoes in terms of possibility, recommendation, purchase intention, and spending more money. If functional, expressive, aesthetic, and mobile needs were satisfied, potential consumers were willing to buy sustainable shoes rather than leather shoes. The findings demonstrated that men's sustainable shoes made with the eco multi-layered material configuration (MCM), which can be a leather substitute, have the potential to attract young male consumers in the future. However, the sustainable shoes in this study still retained a lack of mobility related to fit and comfort as compared to the flexibility of the leather shoes.

In sum, the conceptual framework of the proposed men's sustainable footwear is to provide understanding about the following stages of the IsAcT design process: (a) identify problems and select eco-material, (b) assess eco-materials and create a shoe prototype, and (c) test human trial and wearers' perceptions and acceptance for sustainable footwear. Findings of this comprehensive study support future sustainable footwear research guidelines for improving the field of sustainable product design and development.

CHAPTER 6. LIMITATIONS AND FUTURE RESEARCH

The results of this study should be considered in light of the following limitations. Examining these limitations will provide clear guidance for future research. Further research needs to be performed to enhance the bacteria cellulose (BC) material, such as that used in the current study for improving the feasibility of applying a multi-layered cellulosic material configuration (BC non-woven mat, denim fabric, and hemp fabric) to footwear and effectiveness of combining it with other recycled or eco-materials; this process will assist in creating a variety of wearable products in the IsAcT design process for sustainable shoes. The sustainable shoes in the study were limited to male dress shoes consisting of the multi-layered cellulosic material (MCM), cork, and compacted paper. Future research needs to be conducted to identify optimal solutions to reducing the water absorbency of MCM. Also, as this study did not consider the air gap between the undersides of each layered material for MCM, further examination is needed in this area. It would also be of interest to compare and benchmark the newly proposed material, MCM, with woolen shoes currently being sold by a sustainability practice company (e.g., allbirds). Furthermore, the BC material dyed with natural dyes (onion, grape, and banana skin) or pigments could be manufactured in a variety of colorful MCM footwear styles and products. Based on outcomes of the material properties, further research could investigate a foot thermal sensation model as a useful research tool contributing to the improvement of materials and application of functional design for footwear.

In this study, only three different United States foot sizes (mm) -- 9.5 (270), 10 (275), and 10.5 (280) -- were examined for wear testing. However, depending on the companies, the difference of the shoes' size is approximately ± 0.5 (5 mm), in general. Furthermore, moderating effects of the different shoe sizes did not be considered. Therefore, future examination is needed to consider broad ranges of shoes sizes or customized shoe sizes as well as a moderation effect of shoe sizes by wearers.

The outsoles of sustainable shoes were made of only cork materials which might be accelerated more than rubber or urethane materials. Future study should consider abrasion resistance and impact resistance of outsoles through material testing. Moreover, walking movements were limited to three conditions (flat ground, stair ascent, and stair descent) so that future study need to add a variety of conditions (e.g., uneven surfaces, running, and jumping). Outsole shapes were limited to different shapes of outsoles between a flat shape (the sustainable shoes) and a rounded shape (commercial leather shoes) in the heel part of the shoes. Future study should make the same of outsole shapes when comparing the two shoes. Future study should target enhancing the mobility of sustainable shoes to provide a better fit and comfort to wearers through different insole and outsole materials, including consideration of the thicknesses and shapes of the sustainable materials.

This study explored merely a segment of the population of United States male consumers who are undergraduate and graduate students to accomplish our research purpose, and thus, the results of this study could not be generalized to all United States male consumers. Although the quantitative approach using a survey questionnaire allowed examination of consumers' perceptions about and acceptance of sustainable shoes compared with commercial leather shoes, the small sample sizes (n = 42) were not capable of generating a full understanding of consumers' perceptions and acceptance. However, it is suggested that another survey be conducted with a large sample population to validate our findings. Thus it would be also interesting to examine the wear testing and perceptions of sustainable shoes in United States female wearers of a parallel demographic using a similar research design as the one employed.

CHAPTER 7. IMPLICATIONS AND RECOMMENDATIONS

The findings of this study have noteworthy implications for both the apparel and footwear industry and academic, which is centered on developing a new conceptual framework for sustainable shoe design processes and educating students on how to make sustainable shoes for class/studio learning activities.

Implications for Academia

Academic research investigating a theoretical conceptual framework for sustainable footwear design was sparse in the literature review conducted prior to the study. From a theoretical perspective, the identification of a proposed conceptual framework integrating previous theories or models (cradle-to-cradle design process model, 12 principles of green engineering, and FEA consumer needs) including sustainable clothing and apparel literature provide theoretical implications for the existing sustainable product development.

Theoretically, this study provides an understanding of the target consumers' needs for enhancing awareness of environmental issues and implementing sustainability practices into new sustainable product design and development processes based on the proposed integrated theoretical framework. Moreover, the conceptual framework supplies test guidelines of sustainable shoe prototypes from material testing to wear testing. Academia researchers should consider increasing experimental research on scantly investigated topics in apparel and product development program fields. This study conducted with male students may not only advance the knowledge within the sustainable product development and footwear disciplines, but also provide unique findings for future research recruiting female students or young adults. Pedagogical or teaching guidance may also benefit from the conceptual framework and findings of this research. Because most students have had little experience with shoe design and there has been a lack of pedagogical guidance in shoe design course curricula provided by universities in the United States, educators can use this study's findings to develop sustainable shoe design course content in fashion design and product development curriculum. The sustainable shoe design course could incorporate computer-aided technology (e.g., Sketch-Up and Rhino software) with 3D printing to generate the prototype of shoes. Such a course would be crucial for college students to obtain a variety of relevant knowledge and technical skills to meet needs the modern-day needs in the apparel and footwear industries.

Implications for Apparel and Footwear Industry

This study introduced new, potential material, a multi-layered cellulosic material (MCM) -- BC non-woven mats, denim fabrics, and hemp fabrics -- and detailed the unique properties of MCM that can be utilized to create an array of products (e.g., backpack, clothing, hat, and accessories) in the fashion industries. The selection components and properties of materials in sustainable shoes were considered key elements in the contribution of this study and could be of great benefits to researchers and industrialists. Moreover, sustainable men's dress shoes made with MCM, compressed papers, and cork materials were developed and tested via wear-trial prototypes through kinematic and kinetic approaches; therefore, the material testing and wear testing of sustainable shoes are crucial elements that could guide footwear manufacturers, designers, and researchers in creating new sustainable shoes.

This study contributes significantly to the fundamental knowledge of material science, kinesiology, consumer behavior, and footwear issues in regards to sustainability and mobility. Findings from this study at large can not only contribute to footwear designers' and researchers' processes and designs pertaining to sustainable footwear, but also offer practical implications for marketers aiming to increase revenues, understand wearers' perceptions and acceptance of eco-friendly footwear, and engage sustainable practices in footwear industries. The conceptual framework would also help small sustainable footwear manufacturers and factories to anticipate the characteristics of sustainable shoes and to give guidance on appropriate designs or elements for sustainable footwear in general. Considering growing purchasing power and the large population in the United States, an international market strategy is important for increasing sales of sustainable footwear in a variety of shopping channels for fashion industries.

This study has identified possibilities that would make men's sustainable men's dress shoes made with BC non-woven mats, denim fabrics, hemp fabrics, and cork materials based on the conceptual framework. As for further research, the recommendations are as follows:

1. Academia can benefit from collaborating with inter- and transdisciplinary colleagues, well as footwear industries, to develop the best eco-friendly material combination options that would improve sustainable shoes. The collaborations between members of academia and industry enable enumerable benefits (e.g., sharing information, lack of experiences, budget adherence, time savings, technical skills for industries, partnerships, and internships for students etc.). The collaboration can further play a bridging role to address gaps between academia and industry.
2. Physical properties of material were tested in attempts to improve the BC non-woven mat of MCM; however, the BC non-woven mat still needs to be enhanced in terms of effective treatment (e.g., coating and finishing) for commercial use in a variety of products to better the footwear.
3. Further study should more precisely measure fit and foot shape of the wearer (customizing the sustainable shoe prototype) in order to enhance the performance of shoes. Comparisons should also be conducted with leather shoes with the use of more advanced technological equipment like foot-scanning devices.

4. Future study should be conducted to determine energy efficiency and waste products of other sustainable footwear or apparel by using the IsAcT design process.
5. This study did not consider actual purchasing prices of the sustainable shoes as compared to commercial leather shoes. Consequently, future study could perform a cost analysis of the sustainable shoes made with the MCM material.

The areas identified for further studies are considered quite important as they are directly derived from the findings themselves. It is, therefore, strongly recommended that these aspects be explored to improve the design of and consumers' experience with sustainable shoes in the future research.

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APPENDIX A. INSTITUATIONAL REVIEW BOARD APPROVAL

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CC: Dr. Young-A Lee
1068 LeBaron

From: Office for Responsible Research

Title: Sustainable Shoe Design and Performance Evaluation Using Kinematic and Kinetic Analysis

IRB ID: 17-186

Approval Date: 6/7/2017 **Date for Continuing Review:** 6/6/2018

Submission Type: New **Review Type:** Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, **including the recruitment materials and informed consent documents that have the IRB approval stamp.**
- **Retain signed informed consent documents for 3 years after the close of the study**, when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all research activity if IRB approval lapses,** unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.
- **Complete a new continuing review form** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

APPENDIX B. INFORMED CONSENT DOCUMENT FOR MAIN STUDY

TITIL OF STUDY: Sustainable Shoes' Performance Evaluation

INVESTIGATORS: Changhyun Nam and Dr. Young-A Lee

This is a research study. It has information to help you decide whether or not you wish to participate. Please take your time in deciding if you would like to participate. Please discuss any questions you have about the study or about this form before deciding to participate. This study is funded by United States Environmental Protection Agency (Grant#: SU835733) and was approved by the Institutional Review Board at Iowa State University (IRB ID: 17-186).

INTRODUCTION

The overall aim of this study is to investigate the compatibility of sustainable shoes made of biodegradable natural materials with commercially available leather shoes by comparing wearers' performance and comfort of both shoes. The specific objectives are: (1) to examine wearable shoes' performance of lower body movements while walking on flat ground, ascending stairs, and descending stairs by comparing a pair of men's sustainable shoes with men's casual leather shoes and (2) to assess wearers' subjective perceptions and evaluation of both shoes via survey questionnaire. You are being invited to participate in this study because you are aged 18 years old or over. You should not participate if you currently have (1) back, neck, leg, foot, or arm pain and (or) (2) any musculoskeletal or neurological conditions that would affect your ability to ascend or descend stairs.

DESCRIPTION OF PROCEDURES

If you agree to participate, you will be asked to participate in the following activities:

- Fill out a brief personal information form about your foot measurement, shoe size, height, and weight.
- Shoe wear testing: Have reflective markers placed on your feet, legs, and trunk. You wear both sustainable shoes and commercial leather shoes based on counterbalanced ordering. You will be asked to complete three movements: walking on flat ground, ascending stairs, and descending stairs for three trials in each condition. A total of 45 walking, stair ascent, and stair descent movements will be recorded by video cameras that track the reflective markers. Force platforms positioned in the floor will measure forces between your feet and the ground, and force platforms positioned on the steps of the stairs will measure forces between your feet and the steps.
- After finishing wear testing for each shoe, you will be asked to complete a short survey questionnaire about your acceptance and preference of both shoes.

The data collection occurs in the Biomechanics Lab (Forker 178N). During the data collection session, only the data collector and an assistant (if needed) will be present. These activities will all take place in one day and require approximately 60-90 minutes of your time.

RISKS

While participating in this study, you may experience the following risks. Minor discomfort or skin irritation may occur from reflective markers, commercial leather shoes, and sustainable shoes, so time of application will be minimized as much as possible. Muscle or joint discomfort may occur after completion of the walking, and stair ascent and stair descent movements. You are encouraged to ice any sore muscles and notice us if any pain persists. In order to avoid injury, hands' rails and a spotter will be available to assist you on the staircase if you would begin to lose balance. You will be offered rest periods after each condition to minimize fatigue.

BENEFITS

While there will be no direct benefit to the volunteer, it is hoped that the information gained in this study will benefit society through informing the compatibility of sustainable shoes as an alternative of commercial leather shoes, which can reduce the negative impact to the environment.

COST AND COMPENSATION

You will not have any costs from participating in this study. You will be compensated $10 value of Starbuck gift card upon completion of your participation.

PARTICIPANT RIGHT

Your participation in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. You can skip any questions that you do not wish to answer in a survey questionnaire.

CONFIDENTIALITY

Data analysis and reports of research findings will focus on summary statistics, with no information reported that would enable detection of individual participating subjects. We will be bound by the confidentiality guarantee we have made. Thus, confidentiality will be protected in presentations and publications of research reports. Your identity will remain confidential in any report of the data.

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies including the study sponsor (e.g., EPA), auditing departments of Iowa State University, and Institution Review Board (a committee that reviewers and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: your data will be kept confidential by using alphanumeric identifiers that are unrelated to the subject's name. Your name and information/data will be kept in separate secure locations. The electronic data will be kept on password-protected computers. The individuals who will have immediate access to the identifiable research records include only the principal investigator, Changhyun Nam and his major professor, Dr. Young-A Lee. The data file will be retained for three years after completion of the project and will be destroyed afterwards.

QUESTIONS OR PROBLEMS

You are encouraged to ask questions at any time during this study. For further information about the study, please contact Changhyun Nam, PhD Candidate at (858) 750-8963, cnam@iastate.edu OR Dr. Young-A Lee at (515) 294-7826, ylee@iastate.edu. If you have any questions about the rights of research subjects or research-related inquiry, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-1516, Office of Research Assurances, 2420 Lincoln Way, Suite 202, Ames, Iowa 50011.

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SUBJECT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the signed and dated written informed consent prior to your participation in the study.

Subject's Name (printed) ____

____

(Subject's Signature) (Date)

INVESTIGATOR STATEMENT

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

____

(Signature of Person Obtaining Informed Consent) (Date)

APPENDIX C. PARTICUPANTS' RECRUITMENT VIA E-MAIL

Study Participants Wanted for the Research:
"Performance Evaluation for Men's Sustainable Shoes"

My name is Lyon (Changhyun Nam), a doctoral candidate in apparel, merchandising, and design program. I am conducting a research study to investigate the compatibility of sustainable shoes made with biodegradable cellulosic materials with commercially available leather shoes by comparing wearers' performance and comfort of both shoes. I am seeking study participants for this study.

Who: Healthy Males aged18 years old and over, wearing one of the following U.S-based shoe size: 270mm (U.S. 9.5), 275mm (U.S. 10), and 280mm (U.S. 10.5)

Criteria: You should not participate if you currently have back, neck, leg, foot, or arm pain. Also, you should not participate if you have any musculoskeletal or neurological conditions that would affect your ability to ascend or descend stairs.

What: Participants will participate in the following activities: Informed consent process, shoe wear testing, and a short survey questionnaire. Participates will first perform wear testing of two different types of shoes (sustainable vs. commercial leather shoes) using motion analysis and force platform during walking on flat ground, ascending stairs, and descending stairs. After finishing the wear tests, participants will be asked to complete a short questionnaire about consumer's perceptions and evaluation of both shoes. These activities will all take place one day and require approximately 60-90 minutes of your time. All results will be kept confidential.

Where: Testing session will be held in the Biomechanics Laboratory at 178N Forker Building on the Iowa State University campus.

Compensation: All participants will receive a $10 Starbuck gift card.

If you are interested in participating in this study, please contact Changhyun Nam at (858) 750-8963, cnam@iastate.edu.

I hope to hear from you soon!

Thank you.

APPENDIX D. VERBAL ANNOUNCEMENT IN CLASS

My name is Lyon (Changhyun Nam) who is the doctoral candidate in apparel, merchandising, and design program. I am conducting a research study to investigate the compatibility of sustainable shoes made with biodegradable cellulosic materials with commercially available leather shoes by comparing wearers' performance and comfort of both shoes.

I am looking for healthy males aged 18 years old and over to participate in this study. I am particularly looking for male individuals who wear the US - based shoe size of 9.5 (270mm), 10 (275mm), or 10.5 (280mm). This study requires only one time visit to the Biomechanics Lab (Forker Building, 178N) to participate in shoe wear testing and a short survey questionnaire. It will take approximately 60-90 minutes to complete the study session.

Important notices: You should not participate if you currently have back, neck, leg, foot, or arm pain. Also, you should not participate if you have any musculoskeletal or neurological conditions that would affect your ability to ascend or descend stairs.

All participants will receive a $10 value of Starbuck gift card as compensation.

If you are interested in participating in this study, please contact Changhyun Nam at (858) 750-8963, cnam@iastate.edu.

I hope to hear from you soon!

Thank you.

APPENDIX E. PARTICIPANTS’ RECRUITMENT FLYER

Participants Wanted for the Research!

To investigate the compatibility of sustainable shoes made with biodegradable cellulosic materials with commercially available leather shoes by comparing wearers’ performance and comfort of both shoes.

Title: WEARABLE PERFORMANCE FOR MEN’ SHOES

Who: Healthy Males over 18 years old or older, a shoe size among sizes 270mm (U.S. 9.5), 275mm (U.S. 10), and 280mm (U.S. 10.5) for 30 males.

Criteria: You should not participate if you currently have back, neck, leg, foot, or arm pain. Also, you should not participate if you have any musculoskeletal or neurological conditions that would affect your ability to ascend or descend stairs.

What: participants will be evaluated by motion analysis and force platform during walking on flat ground, ascending stairs, and descending stairs with two type of shoes. After finishing tests, each participant will be asked to short questionnaire about consumer’s perceptions and evaluation of both shoes. Therefore, it takes approximately an hour to complete all tests. All results will be kept confidential.

Where: Testing session will be held in the Biomechanics Laboratory at 178N Forker Building on the Iowa State University campus.

Compensation: All participants will receive a $10 Starbuck gift card.

Contact: Lyon (Changhyun Nam) at (858) 750-8963, cnam@iastate.edu for additional information.

APPENDIX F. CONFIRMATION OF APPOINTMENT TO PARTICIPANTS

Use for both the pilot and main study

To:
Email:
Phone:

Thank you for your interest in participating in the research study titled "Sustainable shoe performance evaluation." A researcher will meet you in the lobby of the **Forker Building and escort you to the lab located at 178N Forker Building.** Your appointment time to meet the researcher is scheduled for:

Date:
Time:
Location: **178N Forker Building lobby** located at 534 Wallace Road. Ames, IA 50011

Campus map: https://www.google.com/maps/place/Forker+Bldg,+534+Wallace+Rd,+Ames,+IA+50011/@42.0267438,-93.6424618,17z/data=!3m1!4b1!4m5!3m4!1s0x87ee7098c28cf77d:0x5e9b8b288879a3ce!8m2!3d42.0268097!4d-93.6403143

If you need to cancel your appointment for any reason, please contact Changhyun Nam at cnam@iastate.edu, (858)-750-8963.

APPENDIX G. PILOT STUDY EVALUATION FORM

Directions: Please answer the following questions or make any comments regarding informed consent form, the wear testing protocol and survey questionnaire.

1. How long did it take for you to complete this study including both the wear testing and survey questionnaire?

   _________ minutes

2. Was the consent form clearly stated?

   ___ Yes ___ No

   If no, please provide your suggestions to make the statement more clearly.

3. Were the survey questions understandable?

   ___ Yes ___ No

   If no, please indicate the question number and what needs to be clarified.

Question No.	Comments

4. Were the scales (rankings) used to access each item in the survey understandable?

   ___ Yes ___ No

   If no, please provide your suggestions to make the scales easier to understand.

Question No.	Comments

5. Overall, what would you like to suggest to improve the survey questionnaire?

6. Overall, was the wear testing procedure easy to follow?

   ___ Yes ___ No

   If no, please provide your suggestions to make the wear testing procedure more effective.

Thank you for your assistance with this pilot study.

APPENDIX H. WEAR TESTING PROTOCOL

Pre-experiment and warming up (10 minutes)

Each participant brought his own sleeveless t-shirt and short pants or compression t-shirt and pants (if not, we can provide them including sock).

- Running on treadmill – 5minutes (normal own speed)
- Stretching – 5minutes

Survey Questionnaire (10 minutes)

Each participant took survey Questionnaire including personal information and open-ended questions

Experiment (65 minutes)

1) Measurement (5 minutes)

The participant's height, weight, length and width of foot (right and left foot) was measured using a scale machine and foot measurement tool.

2) Shoes assignment (5 minutes)

The participant was assigned either a pair of sustainable shoes or commercial leather shoes based on counterbalanced ordering.

3) Marker placement (5 minutes)

21 retroreflective markers (10 mm diameter) with an adhesive surface were placed at the anatomical points at his shoulders and in lower body to capture your movements. Also, each participant stood on a center of the kinematic and kinetic approach settings to recognize his markers with a motion analysis system.

4) Three sequential walking tests for both shoes (45 minutes)

After that, a participant performed several sequential walking tests on three different movements such as walking on flat ground, ascending stairs, and descending stairs (step height 18.5cm, tread depth 29.5m) at kinematic and kinetic approach settings.

For wear testing, participant wear each pair of shoes (sustainable shoes and commercial leather shoes) and sock provided by a researcher assigned while walking on three different walking movements (flat ground, ascending stairs, and descending stairs) based the counterbalanced ordering. A total of 45 walking, stair ascent, and stair descent movements were recorded by video cameras that track the reflective markers. Force platforms positioned in the floor measured forces between the participants' feet and the ground, while force platforms positioned on the steps of the stairs measured forces between the participants' feet and the steps.

Survey Questionnaire (15 minutes)

After each wear testing, the participant was given a short survey questionnaire from sections 3 to 6 to fill out your perceptions and evaluation with each pair of shoes using Qualtrics.

APPENDIX I. COUNTERBALANCED ORDERING

Subject#	First shoes	Second shoes	Shoes A			Shoes B		
1	A	B	flat	up	down	down	flat	up
2	B	A	flat	down	up	down	up	flat
3	A	B	up	down	flat	up	flat	down
4	B	A	up	flat	down	up	down	flat
5	A	B	down	up	flat	flat	down	up
6	B	A	down	flat	up	flat	up	down
7	A	B	flat	up	down	down	flat	up
8	B	A	flat	down	up	down	up	flat
9	A	B	up	down	flat	up	flat	down
10	B	A	up	flat	down	up	down	flat
11	A	B	down	up	flat	flat	down	up
12	B	A	down	flat	up	flat	up	down
13	A	B	flat	up	down	down	flat	up
14	B	A	flat	down	up	down	up	flat
15	A	B	up	down	flat	up	flat	down
16	B	A	up	flat	down	up	down	flat
17	A	B	down	up	flat	flat	down	up
18	B	A	down	flat	up	flat	up	down
19	A	B	flat	up	down	down	flat	up
20	B	A	flat	down	up	down	up	flat
21	A	B	up	down	flat	up	flat	down
22	B	A	up	flat	down	up	down	flat
23	A	B	down	up	flat	flat	down	up
24	B	A	down	flat	up	flat	up	down
25	A	B	flat	up	down	down	flat	up
26	B	A	flat	down	up	down	up	flat
27	A	B	up	down	flat	up	flat	down
28	B	A	up	flat	down	up	down	flat
29	A	B	down	up	flat	flat	down	up
30	B	A	down	flat	up	flat	up	down
31	A	B	flat	up	down	down	flat	up
32	B	A	flat	down	up	down	up	flat
33	A	B	up	down	flat	up	flat	down
34	B	A	up	flat	down	up	down	flat
35	A	B	down	up	flat	flat	down	up
36	B	A	down	flat	up	flat	up	down
37	A	B	flat	up	down	down	flat	up
38	B	A	flat	down	up	down	up	flat
39	A	B	up	down	flat	up	flat	down
40	B	A	up	flat	down	up	down	flat
41	A	B	down	up	flat	flat	down	up
42	B	A	down	flat	up	flat	up	down

Note. shoes A= sustainable shoes; shoes B= leather shoes; flat = flat ground walking; up = ascending stairs walking, down = descending stairs walking.

APPENDIX J. PERSONAL INFORMATION FORMs

Participant's name (#): **Date:**

Assistant' name:

- What size of shoes do you typically wear? __________ US size
- What is your foot dominance? (1) Left (2) Right
- Have you ever had surgery on your legs or foot?

(1) Yes ___________________________________ (2) No

MEASUREMENT

- Length, arch, and width of participant's right foot? — _______, ________, and_______
- Length, arch, and width of participant's left foot? — _______, ________, and_______
- Participant's height in feet and inches? — __________and__________
- Participant's weight in pounds? — __________pound
- Testing shoes sizes? — __________ U.S size

TRIAL ORDERING

Shoes A or B	Trials	walking on flat ground	ascending stairs	descending stairs
A or B	trial #1	1, 2, 3	1, 2, 3	1, 2, 3
A or B	trial #2	1, 2, 3	1, 2, 3	1, 2, 3
A or B	trial #3	1, 2, 3	1, 2, 3	1, 2, 3
A or B	trial #1	1, 2, 3	1, 2, 3	1, 2, 3
A or B	trial #2	1, 2, 3	1, 2, 3	1, 2, 3
A or B	trial #3	1, 2, 3	1, 2, 3	1, 2, 3

APPENDIX K. SURVEY QUESTIONNAIRE

THE FOLLOWING SECTIONS 1 AND 2 WILL NEED TO BE COMPLETED BEFORE STARTING WEAR TESTING OF THE SHOES.

Section 1: About Yourself

Direction: The following questions will help us gain a better understanding of you as a participant in this study.

Q1. What year were you born?

Q2. What is your ethnicity? Check all that applies to you.

- Caucasian/ European American
- African American
- American Indian/Alaska Native
- Asian
- Native Hawaiian and other Pacific Islander
- Hispanic American/ Latino
- Others, please specify

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Section 2: Your thoughts

Direction: Please fill in the blanks about your thought.

Q1. What are the 3-words that first come to your mind when you hear the word **"sustainable/ biodegradable shoes"**?

1st words

2nd words

3rd words

Q2. What do you think **the benefits of wearing sustainable casual/dress shoes** are? Please write down your response below.

Q3. If you would like **sustainable casual/dress shoes** to be **unique** to other leather shoes, what features would you like to see? Please provide your response below (e.g., functional, expressive, aesthetic, and environmental features).

Q4. Please rate the importance of the following features for **men' sustainable casual/dress shoes,** using a 5-point Likert scale, "1" = being the least important to "5" = being the most important.

	Being the least important	Being low important	Being natural	Being important	Being the most important
Functional features (i.e., fit, comfort, protection, mobility)	○	○	○	○	○
Expressive features (i.e., masculine appearance, brand name, fashion trends)	○	○	○	○	○
Aesthetic features (i.e., color, design, visual appeal)	○	○	○	○	○
Environmental features (i.e., recycled/reused materials, eco-friendly materials, biodegradable materials)	○	○	○	○	○

Direction: Please first click in Yes or No. Then fill in the blanks with your reasoning.

Q5. In the past, have you purchased shoes made of sustainable materials (e.g., recycling/reused, organic, biodegradable materials)?

Yes, please provide your purchasing reason

No, please provide your reason

Q6. Are you willing to pay more for the shoes made of sustainable materials (e.g., recycling/ reused, organic, biodegradable materials)?

Yes, please provide your reason

No, please provide your reason

Q7. How much are you willing to pay more for the shoes made of sustainable materials compared to casual/dress shoes made of leather? Please move a slider for the percentage that best represents your willingness.

0 5 10 15 20 25 30 35 40 45 50

Percentage (%)

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THE FOLLOWING SECTIONS 3 TO 7 WILL NEED TO BE COMPLETED AFTER COMPLETING WEAR TESTING OF BOTH SHOES.

You were randomly assigned to both shoes:

(A) Sustainable shoes
(B) Leather shoes

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A. SUSTAINABLE SHOES

Section 3: Functional needs (A: sustainable shoes)

Direction: Please rate the following functional needs that are important to you when purchasing and/or wearing the sustainable shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. The comfort of sustainable shoes should be improved.	O	O	O	O	O
Q2. The fit of sustainable shoes should be improved.	O	O	O	O	O
Q3. The durability of sustainable shoes should be improved.	O	O	O	O	O
Q4. The ventilation quality (breathable-air permeability) of sustainable shoes should be improved.	O	O	O	O	O
Q5. The insulation quality (optimal temperature inside) of sustainable shoes should be improved.	O	O	O	O	O
Q6. The sustainable shoes should be light weight.	O	O	O	O	O
Q7. The sustainable shoes should be easy to put on and take off.	O	O	O	O	O
Q8. Overall, the functional needs of sustainable shoes should be improved.	O	O	O	O	O

Q9. Do you need any other functional design characteristics that were not addressed above to be featured in the sustainable shoes (A)? Please describe here.

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Section 4. Comfort and fit (A: Sustainable shoes)

Direction: The following statements address your perception about the sustainable shoes' comfort and fit during three different movements (walking flat ground, ascending stairs, descending stairs). Please click your response to each question, using 5-point Likert scale, "1" = very poor to "5" = very good.

	Very poor	Poor	Fair	Good	Very good
Q1. How well do the sustainable shoes fit while walking on flat ground?	○	○	○	○	○
Q2. How well do the sustainable shoes fit while ascending stairs?	○	○	○	○	○
Q3. How well do the sustainable shoes fit while descending stairs?	○	○	○	○	○
Q4. How well do the sustainable shoes fit overall?	○	○	○	○	○
Q5. How comfortable are the sustainable shoes while walking on flat ground?	○	○	○	○	○
Q6. How comfortable are the sustainable shoes while ascending stairs?	○	○	○	○	○
Q7. How comfortable are the sustainable shoes while descending stairs?	○	○	○	○	○
Q8. How comfortable are the sustainable shoes overall?	○	○	○	○	○

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Section 5: Expressive needs (A: Sustainable shoes)

Direction: Please rate the following expressive needs that are important to you when purchasing and/or wearing the sustainable shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. Wearing the sustainable shoes helps me look better than other men.	○	○	○	○	○
Q2. The sustainable shoes should make me look fashionable.	○	○	○	○	○
Q3. The sustainable shoes should make me look professional.	○	○	○	○	○
Q4. Wearing the sustainable shoes helps me convey my kind identity as a gentleman.	○	○	○	○	○
Q5. Wearing the sustainable shoes helps me feel more masculine.	○	○	○	○	○
Q6. Wearing the sustainable shoes helps with my self-image as a mature young adult.	○	○	○	○	○
Q7. I am willing to play an important role of conveying the importance of wearing the sustainable shoes to other men.	○	○	○	○	○
Q8. Overall, the expressive needs of sustainable shoes should be improved.	○	○	○	○	○

Q9. Do you need any other expressive design characteristics that were not addressed above to be featured in the sustainable shoes (A)? Please describe here.

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Section 6: Aesthetic needs (A: Sustainable shoes)

Direction: Please rate the following aesthetic needs that are important to you when purchasing and/or wearing the sustainable shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. The color of sustainable shoes should be improved.	○	○	○	○	○
Q2. The style of sustainable shoes should be improved.	○	○	○	○	○
Q3. The texture of sustainable shoes should be improved.	○	○	○	○	○
Q4. The uniqueness of sustainable shoes should be improved.	○	○	○	○	○
Q5. An unique design feature of sustainable shoes should be added.	○	○	○	○	○
Q6. The sleek design of sustainable shoes should be improved.	○	○	○	○	○
Q7. The masculine design of sustainable shoes should be improved.	○	○	○	○	○
Q8. Overall, the aesthetic needs of sustainable shoes should be improved.	○	○	○	○	○

Q9. Do you need any other aesthetic design characteristics that were not addressed above to be featured in the sustainable shoes (A)? Please describe here.

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Section 7: Wearer's acceptance for sustainable shoes (A)

Direction: The following statements address wearer's acceptance for sustainable shoes. Please indicate the level of your agreement on the following statements, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
Q1. It is possible that I will buy the sustainable shoes with eco-friendly materials.	O	O	O	O	O
Q2. I recommend that friends or families buy the sustainable shoes.	O	O	O	O	O
Q3. I will consider purchasing the sustainable shoes.	O	O	O	O	O
Q4. I am willing to pay more money for the sustainable shoes.	O	O	O	O	O

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Continue to participate in Section 3-7 (B)

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Section 3: Functional needs (B: leather shoes)

Direction: Please rate the following functional needs that are important to you when purchasing and/or wearing the leather shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. The comfort of leather shoes should be improved.	○	○	○	○	○
Q2. The fit of leather shoes should be improved.	○	○	○	○	○
Q3. The durability of leather shoes should be improved.	○	○	○	○	○
Q4. The ventilation quality (breathable-air permeability) of leather shoes should be improved.	○	○	○	○	○
Q5. The insulation quality (optimal temperature inside) of leather shoes should be improved.	○	○	○	○	○
Q6. The leather shoes should be light weight.	○	○	○	○	○
Q7. The leather shoes should be easy to put on and take off.	○	○	○	○	○
Q8. Overall, the functional needs of leather shoes should be improved.	○	○	○	○	○

Q9. Do you need any other functional design characteristics that were not addressed above to be featured in the leather shoes (B)? Please describe here.

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Section 4. Comfort and fit (B: Leather shoes)

Direction: The following statements address your perception about the leather shoes' comfort and fit during three different movements (walking flat ground, ascending stairs, descending stairs). Please click your response to each question, using 5-point Likert scale, "1" = very poor to "5" = very good.

	Very poor	Poor	Fair	Good	Very good
Q1. How well do the leather shoes fit while walking on flat ground?	O	O	O	O	O
Q2. How well do the leather shoes fit while ascending stairs?	O	O	O	O	O
Q3. How well do the leather shoes fit while descending stairs?	O	O	O	O	O
Q4. How well do the leather shoes fit overall?	O	O	O	O	O
Q5. How comfortable are the leather shoes while walking on flat ground?	O	O	O	O	O
Q6. How comfortable are the leather shoes while ascending stairs?	O	O	O	O	O
Q7. How comfortable are the leather shoes while descending stairs?	O	O	O	O	O
Q8. How comfortable are the leather shoes overall?	O	O	O	O	O

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Section 5: Expressive needs (B: Leather shoes)

Direction: Please rate the following expressive needs that are important to you when purchasing and/or wearing the leather shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. Wearing the leather shoes helps me look better than other men.	O	O	O	O	O
Q2. The leather shoes should make me look fashionable.	O	O	O	O	O
Q3. The leather shoes should make me look professional.	O	O	O	O	O
Q4. Wearing the leather shoes helps me convey my kind identity as a gentleman.	O	O	O	O	O
Q5. Wearing the leather shoes helps me feel more masculine.	O	O	O	O	O
Q6. Wearing the leather shoes helps with my self-image as a mature young adult.	O	O	O	O	O
Q7. I am willing to play an important role of conveying the importance of wearing the leather shoes to other men.	O	O	O	O	O
Q8. Overall, the expressive needs of leather shoes should be improved.	O	O	O	O	O

Q9. Do you need any other expressive design characteristics that were not addressed above to be featured in the leather shoes (B)? Please describe here.

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Section 6: Aesthetic needs (B: Leather shoes)

Direction: Please rate the following aesthetic needs that are important to you when purchasing and/or wearing the leather shoes. Please click your response that best describes the level of your agreement with each statement, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Q1. The color of leather shoes should be improved.	○	○	○	○	○
Q2. The style of leather shoes should be improved.	○	○	○	○	○
Q3. The texture of leather shoes should be improved.	○	○	○	○	○
Q4. The uniqueness of leather shoes should be improved.	○	○	○	○	○
Q5. An unique design feature of leather shoes should be added.	○	○	○	○	○
Q6. The sleek design of leather shoes should be improved.	○	○	○	○	○
Q7. The masculine design of leather shoes should be improved.	○	○	○	○	○
Q8. Overall, the aesthetic needs of leather shoes should be improved.	○	○	○	○	○

Q9. Do you need any other aesthetic design characteristics that were not addressed above to be featured in the leather shoes (B)? Please describe here.

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Section 7: Wearer's acceptance for leather shoes (B)

Direction: The following statements address Wearer's acceptance for leather shoes. Please indicate the level of your agreement on the following statements, using 5-point Likert scale, "1" = strongly disagree to "5" = strongly agree.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
Q1. It is possible that I will buy the leather shoes with eco-friendly materials.	O	O	O	O	O
Q2. I recommend that friends or families buy the leather shoes.	O	O	O	O	O
Q3. I will consider purchasing the leather shoes.	O	O	O	O	O
Q4. I am willing to pay more money for the leather shoes.	O	O	O	O	O

Your contribution to this research is greatly appreciated.

THANK YOU FOR YOUR PARTICIPATION

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APPENDIX L. PROTOTYPE OF MEN'S SUSTAINABLE SHOES

Image A. Prototype shoes with MCM and cork materials

Image B. Different Views of Prototype shoes